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INTRODUCTION TO RADIOLOGICAL
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INTRODUCTION TO RADIOLOGICAL DEFENSE PLANNING

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I INTRODUCTION

The planning of radiological defense (RADEF) countermeasures, for developing either requirements for the design of RADEF systems or operational requirements and limitations, is based on the availability of basic radiological data and on techniques for applying the data to RADEF problems and situations.

The basic radiological data and its parameters are:

1. a decay curve representing the decrease of the radiation intensity (r/hr) with time after a detonation
2. the standard intensity I_s , which is radiation intensity in r/hr corrected to one hour after detonation
3. the time of arrival of fallout

The major parameters involved in the RADEF planning techniques are:

1. the shelter shielding residual number RN_1^*
2. the shelter stay (or exit) time t_e (same¹ as the entry time to an outside radiation field)
3. the postattack operational residual number RN_2 for decontamination crews, evacuation, or other early postattack countermeasures
4. the long term postattack residual number RN_3 (the decontamination residual number, the effective shielding residual number of buildings and other material, or a combination of the two)

* The residual number is the ratio of the exposure dose (or dose rate) received at a given location when a countermeasure is applied to that received without the countermeasure. The numerical value of the residual number depends on the reference location and exposure conditions that are selected for evaluation. In this report, the reference condition is the exposure (dose or dose rate) at three feet above a uniformly contaminated real open land area.

The subscript numerals for each of the designated residual numbers refer to a time period. Thus, in designating RN_1 for the shelter, it is tacitly assumed that there is a time period to be considered from fallout arrival until people leave a shelter. The definition of the residual number emphasizes applications to the evaluation of operational RADEF systems, and therefore the RN_1 value for a shelter is not, except for isolated situations, equal to the inverse value of the commonly used protection factor.

The residual numbers may be complex quantities for a real RADEF system and include considerations of shielding, exposure times, decontamination, and other postattack civil defense operations in which exposure control procedures are involved. The numerical values of the residual numbers depend on the radiation source geometry and location in the radiation field assumed for computing (or measuring) the potential exposure dose or dose rates. In this report, reference location of measure and source geometry is defined as the exposure (dose or dose rate) at three feet above a uniformly contaminated real open land area. Thus the RN_1 for a shelter would be the ratio of the dose rate in the shelter (say, near the door or exterior wall) to that at three feet above the surface at a nearby open field (assumed to receive the same fallout deposit as the area around the shelter).

The values of RN_2 and RN_3 comprise a combination of exposure time considerations, the attenuation of radiation by shielding, decontamination effectiveness, and (perhaps) the reduction in dose rates owing to weathering. The average attenuation factors are designated as A_1, A_2, \dots for locations and exposure times and are evaluated in the same way as RN_1 for the shelter. Generally, the attenuation factors are restricted to the attenuation resulting from the presence of existing structures. The ratio of the residual dose rate after decontamination or the postattack construction of shielding barriers to the initial dose rate is designated as F . Thus, for locations in which the dose rate has been altered by postattack countermeasures and which are occupied on a scheduled basis (after the initial period in shelter), the value of RN_3 as defined here is equal to the product $A_3 F$.

The major planning criteria for RADEF operations include

1. an operational exposure dose limit D^*
2. the concept of a time-phased use of radiological countermeasure systems
3. the specification of postattack countermeasure routines

The use of the various factors listed above in the solution of RADEF problems is described in the following sections. Data for making planning calculations for a variety of RADEF situations are presented in the form of graphs with illustrative calculations.

II RADEF SYSTEM PARAMETER RELATIONSHIPS

The most important measurable quantity that is related to the radiological hazard from exposure of people, animals, plants, and insects is the exposure dose. The exposure dose is calculated from a decay curve; the exposure dose for the RADEF planning techniques described below was calculated from the curve of Figure 1, as taken from Ref. 1.* The exposure dose is presented in Figure 2 as a set of dose-rate multiplier curves; the dose-rate multiplier is defined mathematically by

$$\text{DRM} = \frac{1}{I_s} \int_{t=1 \text{ hr}}^t I(t) dt \quad (1)$$

where $I(t)$ represents the decay curve.

The planning data were prepared for the case of an effective fallout arrival time of one hour after detonation. A curve for making corrections to I_s of a given planning curve for other effective fallout arrival times is also presented. For convenience of computation, the effective fallout arrival time, rather than the true fallout arrival time, is used to estimate the exposure dosage during the fallout period. This selection was made consistent with the calculative method used to estimate exposure dosages after fallout cessation. Mathematically, the use of an effective fallout arrival time requires the assumption of instantaneous fallout deposition at a given time and a pseudo radiation intensity associated with that time as calculated from I_s and the decay curve. Because the calculated exposure dosage must coincide approximately with the true exposure dosage starting with the time of fallout arrival, the effective fallout arrival time is later than the true arrival time.

The time phasing of radiological countermeasures involves the use of shelters during the attack and transattack period of a war; this is

* Figures are grouped at the end of the report, beginning on page 23.

designated as the first period. At a given location, this in-shelter period lasts at least until brief exposures outside of shelter are feasible. Postattack countermeasures can then be initiated. This initial recovery period is designated as the second period. At some time later (at the same location) all surviving people in shelters can exit from shelter to carry out further recovery countermeasures and live in the environment for the remainder of their lives. This phase of recovery is designated as the third recovery period.

A feasible RADEF system is one in which the exposure dose of a person in a given situation does not exceed an exposure-dose limit, designated D^* , over all three time periods. This restriction is represented in general by

$$D^* \geq RN_1 D_1 + RN_2 D_2 + RN_3 D_3 \quad (2)$$

where D_1 , D_2 , and D_3 are the "open" field (outside) exposure doses that would be received by a person standing at the location in the radiation field from the time of fallout through the three consecutive exposure periods. The limiting time for D_3 (i.e., the long term dose corresponding to the "infinity" dose), according to Figure 2, is about 20,000 hours or 2.3 years. The three exposure doses in Eq. (2) are calculated from the dose rate multiplier curve; substituting the multipliers for the exposure doses gives Eq. (2) as

$$D^* \geq I_s RN_1 \Delta DRM_1 + I'_s RN_2 \Delta DRM_2 + I''_s RN_3 \Delta DRM_3 \quad (3)$$

where the ΔDRM quantities are differences in the dose-rate multipliers for the three consecutive time periods. The primes on I_s indicate that the value of I_s may vary for each of the three time periods owing to population movements. However, in many applications of Eq. (3), the same value of I_s is used; this use of I_s implies the assumption that the people do not move or that the calculation applies to a location rather than to individuals.

One of the major difficulties in applying Eq. (3) to RADEF problems and situations is the selection of appropriate criteria for evaluating D^* . While it may be desired that D^* be as low as possible (which would require that RN_1 , RN_2 , and RN_3 also be low), the required low residual number combinations may not be obtained in practice. Rather than select arbitrary values for D^* in Eq. (3) to determine what

residual number combinations are required, it is more practical to select broad categories of radiation injury to humans as a basis for establishing D^* values for use in Eq. (3). This will permit the determination of sets of residual number combinations for RADEF systems that could be used to predict which broad category of radiation injury would result to the people using a given RADEF system.

The three broad categories of radiation injury and the associated exposure dose for each injury category are:

1. Radiation injury from which recovery of all persons so exposed is virtually certain. The upper-limit exposure dose for this category is currently accepted^{*} as being about an effective residual dose (ERD) of 200 r.
2. Radiation injury that results in death to virtually all people so exposed (the chance of recovery is practically zero). The lower-limit exposure dose for this category is about 600 r in four days or 1,000 r in one month.
3. Radiation injury from which recovery is uncertain or unknown.

Within the limits of certainty of the known effects, people having exposure doses within the first radiation injury category would be capable of performing work without medical help. Virtually all those in the second injury category would become fatalities within several weeks. People in the third radiation injury category would become radiation casualties; these people would generally not be able to carry out normal activities and would require medical or other assistance. Some would eventually recover to some degree, and the remainder would die; the proportion of recovery, in different degrees, and fatalities would depend on the effectiveness of medical treatment and other factors.

* By definition, ERD is the accumulated dose corrected for such biological repair or recovery as has occurred at a specific time; it is derived by use of the biological recovery formula. A person who has received a particular ERD is presumed to display approximately the same signs and symptoms of radiation injury as would be anticipated following a brief dose of the same magnitude. According to Ref. 2, the biological recovery rate is 2.5 percent per day of 90 percent of the exposure dose; the remaining 10 percent of the exposure dose is not repaired.

Since one purpose in the planning of RADEF systems is to maximize the number of people that would fall in the first injury category, a RADEF system is defined as a feasible system if it has the appropriate set of residual number values that, for a given value of I_s , will limit the exposure dose to each individual using the system to 200 r, ERD (or less). The limit of feasibility of a system is one in which D^* is equivalent to exactly 200 r, ERD; the planning calculations are concerned with the residual number combinations of the RADEF systems at the limit of feasibility, as defined. The limiting exposure doses D^* , corresponding closely to the 200 r, ERD, dose are:

190 r in one week
270 r in one month
700 r in one year

These exposure-dose criteria for a feasible RADEF system are illustrated in Figure 3 in terms of a plot of the allowed entry times into a radiation field against the product of the standard intensity and the residual number. If the value of t_e is taken as the effective fallout arrival time, then RN becomes the maximum value of the shielding residual number of a shelter (RN_1) for the case in which the shelter would be occupied for a very long time (i.e., possibly up to 2.3 years).

III RADEF SYSTEM OPERATIONAL ROUTINES

Application of the basic relationships among the RADEF system parameters requires specification of operational routines within the time-phasing concept. The simplest possible RADEF system routine is given in the preceding paragraph: the people enter shelter, stay there for a long period of time, and then come out. In this case, for the selected exposure-dose criteria of 190 r/week-270 r/month-700 r/year, the curve in Figure 3 shows for an effective fallout arrival time of one hour after detonation that

$$RN_1 = \frac{63}{I_s} \quad (4)$$

This simple operational routine requires only a shelter but is an unacceptable RADEF system; it is unacceptable not because stocks of water and food and other living necessities that must last for a long period of time would have to be made available, but because the recovery of the socioeconomic functions of the people after a nuclear war would require the earliest possible exit from shelter in the postattack period. In other words, the people would enter shelter so they may exist during the period of greatest hazard and come out as soon and as healthy as possible to recover what they can of their homes and businesses and of the whole national social structure.

The basic computations for each routine assume an effective fallout arrival time of one hour after detonation and fallout from a single detonation. At many locations the fallout from a single detonation would be expected to contribute most of the intensity after fallout cessation. The locations most likely to receive large amounts of fallout from each of several explosions are those downwind from large missile sites. If the detonations occurred over a period of about 24 hours, the differences in decay rates would be such that at 100 hours after the first detonation and about 76 hours after the last the relative contributions from each would thereafter remain within 20 percent of each other. In other words, at times longer than 100 hours after the first detonation, the radiation from all the deposited fallout is decreasing at about the same rate. If I_s is determined from radiation measurements made at 100 hours after the first detonation using the

first detonation as the reference time, the exposure dose and shelter shielding requirements for the first period would be overestimated to a small degree. The dose-rate multipliers for 76 and 100 hours, for an effective fallout arrival time of one hour, are 2.693 and 2.823, respectively. Thus, if I_s values for the first and last detonations are the same, the average dose-rate multiplier is 2.758. This is very close to the dose-rate multiplier for 88 hours, the average of 76 and 100 hours. But the maximum overestimate in using the single detonation dose-rate multiplier for the first detonation in this case would be about five percent.

In all the RADEF operational routines considered, the occupation of shelter during the first period is automatically included in the routine. The standard RADEF operational routines considered are described in the following pages.

Operational Routine 1

The population, in shelter having a residual number of RN_1 , exits at time t_e to an outside environment having an effective residual number RN_3 . For this case, Eq. (3) becomes

$$D^* = I_s RN_1 \Delta DRM_1 + I'_s RN_3 \Delta DRM_3 \quad (5)$$

Here the value of RN_1 is determined by the available shelter, and the value of RN_3 would be determined by the shelter available in the area where the people lived (houses, offices, natural decontamination effects, etc.) and by decontamination efforts of other people. The relationship given by Eq. (5) does not include receiving exposure doses for conducting special operations such as decontamination, rescue, damage repair, etc.

The relationships among t_e , RN_1 , RN_3 , and I_s are plotted in Figures 4 through 21; data for other selected values of these parameters can be readily obtained from the curves. For example, if compatible values of RN_3 and t_e as a function of I_s were desired for an RN_1 value of 0.025 (protection factor of 40), the appropriate values of RN_3 can be taken from Figures 9 through 13 and plotted directly on corresponding Figures 4 through 8 for each selected value of t_e . Plots similar to those of Figures 14 through 21 can then be made.

The graphs in Figures 4 through 8 give the maximum value of RN_3 for various values of RN_1 and I_s for shelter stay times of one day, three and one-half days, one week, two weeks, and one month, respectively. The curves for a one-week shelter-stay time (or longer) show that the RADEF systems become nonfeasible at given values of I_s independent of the RN_3 values below a given value. In these cases, the exposure-dose limit for the first category of radiation injury is exceeded in the shelter.

Example applications of Figures 4 through 8:

1. Given a shelter with $RN_1 = 0.01$, $I_s = 5,000$ r/hr, and a shelter stay of one week, what is the maximum value of RN_3 ? Using Figure 6, find the intercept of the $RN_1 = 0.01$ curve with the $I_s = 5,000$ r/hr line, and read the RN_3 value of the point described. The maximum $RN_3 = 0.06$.
2. What is the maximum RN_3 if shelters with $RN_1 = 0.001$ were available? Using Figure 6, find the intercept of the $RN_1 = 1 \times 10^{-3}$ curve with the $I_s = 5,000$ r/hr line, and read the RN_3 value of the point described. The maximum $RN_3 = 0.13$.

The graphs of Figures 9 through 13 give the maximum values of RN_1 for selected values of RN_3 , I_s , and shelter stay times of one day, three and one-half days, one week, two weeks, and one month, respectively. These curves also show, for the higher RN_1 values and longer shelter-stay times, that the RADEF system cannot be made feasible by decreasing RN_3 beyond a given value; the RN_1 value at which this occurs is where the various curves of selected RN_3 values join a common curve. The curves also show that for I_s values up to about 10,000 r/hr at one hour a shelter residual number of 0.0001 is essentially a perfect shelter but that RN_3 values of 0.5 to 0.1 are required for making the RADEF system feasible at the indicated I_s value and for shelter stay times of one to two weeks.

Example applications of Figures 9 through 13:

1. Given a fallout area with $I_s = 5,000$ r/hr and an attainable $RN_3 = 0.03$, what is the maximum RN_1 of the shelter if shelter stay is limited to one week? Using Figure 11, find the intercept of the $RN_3 = 0.03$ curve with the $I_s = 5,000$ r/hr line, and read the maximum RN_1 value of the point described. The maximum $RN_1 = 0.0125$.

2. What is the maximum RN_1 if I_s were equal to 10,000 r/hr?
Using Figure 11, find the intercept of the $RN_3 = 0.03$ curve with the $I_s = 10,000$ r/hr line, and read the maximum RN_1 value of the point described. The maximum $RN_1 = 0.005$.

The graphs of Figures 14 through 21 contain the same information as Figures 4 through 13; in this series of figures, the minimum shelter-stay time is plotted as a function of the standard intensity for a limiting set of RN_1 and RN_3 values. The curves of Figures 14 and 15, for shelters with the higher RN_1 values, show that the RADEF system would be feasible at higher I_s values and earlier exit times if RN_3 were less than RN_1 . However, these curves do not specify how the lower RN_3 could be achieved in the indicated time. In all other cases, the required shelter-stay times increase as I_s increases until the shelter itself becomes the nonfeasible component of the system. At the I_s value where the shelter fails (at $RN_3 = RN_1$), the stay time becomes independent of I_s . The curves of Figures 18 through 21 show the increasing spread in I_s values for shelters with different RN_1 values as RN_3 is decreased. The curves for $RN_3 = 0.5$ would be generally applicable to urban areas where no decontamination was planned, and the curves for $RN_3 = 0.1$ and 0.01 would correspond, respectively, to RADEF systems where a moderate and intensive level of effort to decontaminate outside areas was planned.

Example applications of Figures 14 through 21:

1. Given a shelter with $RN_1 = 0.01$, $I_s = 5,000$ r/hr, and a staging area with $RN_3 = 0.1$, when can people leave the shelter and occupy the staging area? Using Figure 20, find the intercept of the $RN_1 = 0.01$ curve with the $I_s = 5,000$ line, and read the (t_e) value of the point described. The minimum shelter-stay time is 11.3 days.
2. What is the minimum shelter-stay time if shelters with $RN_1 = 0.001$ were available? Using Figure 20, find the intercept of the $RN_1 = 0.001$ curve with the $I_s = 5,000$ line, and read the (t_e) value of the point described. The minimum shelter-stay time is five days.

Operational Routine 2

The population, in shelter having a residual number of RN_1 , exits at the time t_e and evacuates the area with the standard intensity I_s and moves to an area where I'_s is negligible compared to I_s . The time

required for the move is Δt .

Alternate Routine

Decontamination crews, in shelter having a residual number of RN_1 , leave shelter at the time t_e and decontaminate a nearby area with an average decontamination effectiveness of F (the fraction of the initial radiation rate remaining after decontamination). The allowed decontamination exposure time is Δt .

These two operational routines are considered together because the computation of the time limitations involves similar applications of Eq. (3). Estimates of Δt can be made by assuming that the decay rate is no longer rapid when the evacuation or decontamination is started and that $I(t_e)$, the intensity at the time t_e , effectively decreases linearly with time over the time period Δt owing to decontamination or movement to a radiation-free area. If A_2 is designated as the average attenuation factor or shielding residual number for the operation and A_3 is the attenuation factor for the third exposure period, then the limiting exposure-dose equation is

$$D^* = I_s RN_1 \Delta DRM_1 + A_2 (1 + F) I(t_e) (\Delta t / 2) + I'' A_3 F \Delta DRM_3 \quad (6)$$

For the evacuation routine, I'' is taken to be equal to zero (area moved to is assumed to contain no fallout); thus the maximum times of evacuation are estimated from

$$\Delta t = \frac{2(D^* - I_s RN_1 \Delta DRM_1)}{A_2 I(t_e)} \quad (7)$$

The maximum time allowed an individual to participate in decontamination operations is also estimated from Eq. (7) for $F = 0.1$ or less; otherwise, for the decontamination routine, the maximum time of exposure during the operations is estimated from

$$\Delta t = \frac{2 \left[D^* - I_s (RN_1 \Delta DRM_1 + A_3 F \Delta DRM_3) \right]}{A_2 (1 + F) I(t_e)} \quad (8)$$

For poorer shelter (larger RN_1 values), the major difference between Eqs. (7) and (8) involve the factor $(1 + F)$. If the RADEF system planning estimates involve the assumed reoccupation of an evacuated area by the same people that were evacuated, then Eq. (8) is used to estimate Δt . In this case, ΔDRM_3 is calculated from Figure 2 from the time of re-entry up to a time specified by D .

The curves of Figures 22 through 27 show the dependence of the maximum times Δt for evacuation or decontamination on I and RN_1 for operations starting at one day, two days, four days, seven days, fourteen days, and thirty days after attack. The curves apply to the conditions of Eq. (7) where $A_2 = A_3 = 1.0$, and $F = 0$. If an A_2 value of 0.5 for evacuation in vehicles through open country is assumed, the Δt values from the curves would be doubled.

The maximum times allowed for evacuation or decontamination for people initially in shelter with the larger RN_1 values are seen to be almost independent of I ; the routine becomes nonfeasible over a very narrow range of I_s values.

Example applications of Figures 22 through 27:

1. Given a shelter with $RN_1 = 0.01$, $I_s = 5,000$ r/hr, and decontamination begun four days after the attack, what is the maximum decontamination time allowed an individual? Using Figure 24, find the intercept of the 0.01 curve with the $I_s = 5,000$ r/hr line, and read the Δt value of the point described. The maximum allowed decontamination time per man is 4.7 hours.
2. What is the maximum allowed decontamination time if decontamination were delayed until after the seventh day? Using Figure 25, find the intercept of the 0.01 curve with the $I_s = 5,000$ r/hr line, and read the Δt value of the point described. The maximum allowed decontamination time per man is 8.2 hours.
3. What is the maximum allowed decontamination time after the seventh day if the shelter had an $RN_1 = 0.001$? Using Figure 25, find the intercept of the 0.001 curve with the $I_s = 5,000$ r/hr line, and read the Δt value of the point described. The maximum allowed decontamination time per man is 40 hours.

The curves of Figures 28 through 31 show the variation of the starting times for evacuation or decontamination with I for a selected set of operating times Δt for people initially in shelters with RN_1

values of 0.1, 0.01, 0.001, and 0.0001. The curves also apply to the conditions of $A_2 = A_3 = 1.0$, and $F = 0$. The rather narrow range in I_s for feasible routines for the largest RN_1 is emphasized by the curves^s of Figure 28. For the RADEF systems that have shelters with low RN_1 values, the starting time generally increases with I_s . In all cases the feasible systems for the higher I_s values are those with the shortest operating times.

Example applications of Figures 28 through 31:

1. Given a shelter with $RN_1 = 0.01$, $I_s = 5,000$ r/hr, and the time required for evacuation is eight hours, what is the minimum period before evacuation may be started? Using Figure 29, find the intercept of the $\Delta t = 8$ hours curve with the $I_s = 5,000$ r/hr line, and read the t_e value of the point described. The minimum evacuation starting time is 8.1 days.
2. What is the minimum period before evacuation may be started if only four hours are needed for evacuation? Using Figure 29, find the intercept of the $\Delta t = 4$ hours curve with the $I_s = 5,000$ r/hr line, and read the t_e value of the point described. The minimum evacuation starting time is 3.8 days.

The actual feasibility of conducting an evacuation or a decontamination operation within the required times is determined from analysis of specific target areas. For postattack evacuation, this feasibility check would involve the distances to likely reception center areas, the mode and speed of transport of the people from shelters, and other factors. For example, when the food and water stocks of otherwise good shelters become depleted, people would have to evacuate the shelters without regard to the possible radiological limitations of the RADEF systems described and used in this report.

The feasibility of carrying out a decontamination operation to obtain the desired F values within a specified time period is evaluated by means of methods described in Ref. 1 (Vol. II).

Operational Routine 3

Fallout area entry and re-entry routines:

1. Entry into an area covered with fallout from an area with no fallout; entering persons have not yet been exposed to radiation.

2. Re-entry of a previously evacuated area; the evacuated people re-enter the area.
3. Daily re-entry of an area from shelter after staying in shelter a given length of time t_e .

Four curves giving re-entry times for specific assumed shelter conditions and living routines, designated A, B, C, and D, are shown in Figure 32. Under condition A, people with no previous exposure dose enter an area having the standard radiation intensity I_s . After entry, the people stay in buildings (or shelters) with a shielding residual number A_3 of 0.1 for twelve hours each day and spend the remaining twelve hours in areas where the effective reduction in intensity F is 0.5. For these assumed conditions, RN_3 is 0.3, and the limiting exposure dose is given by (neglecting the dose accumulated during the period of re-entry)

$$D^* = I_s RN_3 \Delta DRM_3 \quad (9)$$

The entry times for this condition were determined directly from Figure 3.

Under condition B, all people stay in shelters with an RN_1 of 0.001 for two weeks after attack at which time they evacuate to a fallout-free area at a distance requiring eight hours of travel. After re-entering the area, the people stay in the shelters for twelve hours of each day and spend the rest of the time in areas where the effective reduction in intensity is 0.3. For these postattack exposure conditions, RN_3 is 0.15. The limiting exposure-dose expression for this routine is Eq. (6) with I_s'' set equal to I_s .

Under condition C, all people remain in shelters with an RN_1 of 0.001 until they can come out and resume the same living routine assumed for condition B; the routine in this case is twelve hours each day spent out of shelter where F is 0.3. In this case, the limiting exposure-dose is given by

$$D^* = I_s (RN_1 \Delta DRM_1 + RN_3 \Delta DRM_3) \quad (10)$$

Under condition D, the assumed routine is the same as for condition A except that shelters are available with A_3 values of 0.001

instead of 0.1; after entry, the daily living routine is the same as for conditions B and C. The limiting exposure dose for condition D is given by Eq. (9).

The curves of Figure 32 show that the routines are in the order of D, C, B, and A for obtaining the earliest entry or re-entry time at a given value of I_s or for being feasible RADEF systems at the highest I_s values for a given entry or re-entry time.

Example applications of Figure 32:

1. When can people enter a fallout area with $I_s = 10,000$ r/hr under condition A? Answer: At 100 days.
2. When can people described by condition B re-enter the fallout area? Answer: At 41 days.
3. When can people described by condition C enter the fallout area for the first time? Answer: At 38 days.
4. When can people enter a fallout area with $I_s = 10,000$ r/hr under condition D? Answer: At 36 days.

Because there are many variations in the parameter values for the assumed basic operational routines, the computational method for estimating the entry or re-entry times is described for further applications. In each of Eqs. (6), (9), and (10), the calculation of the times involves the evaluation of ΔDRM_3 along with other terms of the equations for compatibility with the defined values of D^* . In other words, the RADEF system and its operational use in chronological order must be such that the exposure doses do not exceed 190 r in the first week of exposure, 270 r in the first month of exposure, or 700 r in the first year of exposure. This requires, in general, that the three equations be checked to verify that none of the three exposure-dose limits is exceeded.

In Eq. (10), for example, the value of ΔDRM_3 , because of the time limits on D^* , is given by

$$\Delta DRM_3 = DRM^* - DRM_t \quad (11)$$

where DRM_t [given as ΔDRM_1 in Eq. (10)] is the value of the dose-rate multiplier at the appropriate entry time, as shown in Figure 2, and

DRM^* is the dose-rate multiplier for the time to which D^* applies. The paired values are as follows:

D^*	t_e	DRM^*
190	one week	3.035
270	one month	3.424
700	one year	3.919

The three equations for DRM_t resulting from the exposure-dose limits applied to Eq. (10) are:

$$DRM_t = \frac{3.035 RN_3 - (190/I_s)}{(RN_3 - RN_1)} \quad (12)$$

$$DRM_t = \frac{3.424 RN_3 - (270/I_s)}{(RN_3 - RN_1)} \quad (13)$$

and

$$DRM_t = \frac{3.919 RN_3 - (700/I_s)}{(RN_3 - RN_1)} \quad (14)$$

These equations show that DRM_t decreases linearly with $1/I_s$ for given values of RN_1 and RN_3 . One of the three equations controls the value of DRM_t for a different range of values of I_s and RN_3 . Equation (12) controls the values of DRM_t for I_s values less than $206/RN_3$; Eq. (13) controls the values of DRM_t for I_s values from $206/RN_3$ to $869/RN_3$; and Eq. (14) controls the values of DRM_t for I_s values greater than $869/RN_3$. The controlling values for each range are determined by setting Eqs. (12) and (13) equal to each other in one case and Eqs. (13) and (14) equal in the second case, and solving for I_s .

Curves such as those in Figure 32 are determined by selecting a set of I_s values (for a given set of RN_1 and RN_3 values), solving for DRM_t in Eqs. (12), (13), or (14), and reading the time at which the calculated value of DRM_t occurs in Figure 2.

The re-entry time for the routine described by Eq. (6) is determined in much the same way, except that ΔDRM_1 must be fixed by an assumed shelter-stay time of two weeks, and the maximum value of RN_1 must first be determined to be feasible for the 190 r in one-week exposure-dose criteria. After substituting the appropriate parameter values, the three equations for calculating DRM_t values for Eq. (6) are:

$$\text{RN}_1 < 62.6/I_s \quad (15)$$

$$\begin{aligned} 270/I_s = & 3.240 \text{RN}_1 + 3.75 \times 10^{-4} A_2 (1 + F) \Delta t \\ & + \text{RN}_3 (3.424 - \text{DRM}_t) \end{aligned} \quad (16)$$

and

$$\begin{aligned} 700/I_s = & 3.240 \text{RN}_1 + 3.75 \times 10^{-4} A_2 (1 + F) \Delta t \\ & + \text{RN}_3 (3.919 - \text{DRM}_t) \end{aligned} \quad (17)$$

In Eqs. (16) and (17), 3.75×10^{-4} is $I(t_e)/2 I_s$ at fourteen days after detonation (see Figure 1).

The three DRM_t equations that result from Eq. (9) are:

$$\text{DRM}_t = 3.035 - \frac{(190/I_s)}{\text{RN}_3} \quad (18)$$

$$\text{DRM}_t = 3.424 - \frac{(270/I_s)}{\text{RN}_3} \quad (19)$$

and

$$\text{DRM}_t = 3.919 - \frac{(700/I_s)}{\text{RN}_3} \quad (20)$$

The range of I_s values for which each equation of this set controls the DRM_t values is the same as those given for Eqs. (12), (13), and (14).

For a three-phase RADEF system that includes a shelter-stay period, a target decontamination period, and a prolonged target stay period after decontamination, and the parameters RN_1 , RN_2 , and RN_3 are known, Eq. (3) may be directly solved to determine the decontamination starting time for various I_s values and decontamination exposure periods. The values of RN_2 and RN_3 vary with the type of target complex decontaminated and with the details of the scheduling for the (planned) decontamination operation. The value of each may be estimated through use of radiological target-complex analysis methods and the application of decontamination data.

The curves of Figures 33 and 34 give, for various I_s values (without specifying any details of the target complex or the decontamination operation), the decontamination starting time for $RN_2 = 0.7$; for the decontamination period $\Delta t_2 = 8$ hours and $\Delta t_2 =$ two 8-hour periods on successive days; for $RN_3 = 0.1$ and $RN_3 = 0.01$; and for the conditions where $RN_1 = 0.01$ and $RN_1 = 0.001$, respectively. In Figure 33, the limiting I_s for all four curves is dictated by the RN_1 of the shelter [Eq. (15)]. In Figure 34, the limiting I_s for curves A and B basically is determined by the RN_3 value ($RN_3 = 0.1$). The RN_3 ($RN_3 = 0.01$) for curves C and D, on the other hand, is sufficiently low that the limiting I_s is again dictated by the RN_1 of the shelter.

IV CORRECTION TERMS TO THE STANDARD INTENSITY AND EXPOSURE TIMES FOR FALLOUT ARRIVAL TIMES LONGER THAN ONE HOUR

In many fallout situations of interest in the planning of RADEF system requirements and operations, the time of fallout arrival will range from one hour up to perhaps twenty hours after detonation. The later fallout arrival times could decrease considerably the exposure doses to people in shelter, for a given value of I_s , from that estimated for a one-hour effective fallout arrival time.^s This decrease would occur because of the rapid decay of the radiation during the early times after detonation while the fallout particles are still in the air.

Because of the increased number of combinations of variables that result from substitution of the fallout arrival time in the basic exposure-dose equations, a correction factor to the standard intensity was derived. This results in a shift in the I_s coordinate that depends on the assumed values of RN_1 , RN_3 , and the shelter-stay times. The "corrected" standard intensity¹ is³ given by

$$I_s(\bar{t}_a) = I_s \left[\frac{RN_3 + a(1)RN_1}{RN_3 + a(t)RN_1} \right] \quad (21)$$

where

$$a(1) = \frac{DRM_{te}}{(DRM^* - DRM_{te})} \quad (22)$$

and

$$a(t) = \frac{(DRM_{te} - DRM_{ta})}{(DRM^* - DRM_{te})} \quad (23)$$

where DRM_{t_a} is the dose-rate multiplier at the effective fallout arrival time, \bar{t}_a . The values of $a(1)$ and $a(t)$ are plotted as a function of t in Figure 35 for fallout arrival times of one, two, five, ten, and twenty hours after detonation. These correction times are applied to the curves of Figures 4 through 21.

The correction term for the maximum times allowed for evacuation and/or decontamination for effective fallout arrival times longer than one hour is defined by

$$\Delta t(\bar{t}_a) = \Delta t + (RN_1/RN_2)b(t) \quad (24)$$

where

$$RN_2 = A_2(1 + F)/2 \quad (25)$$

and

$$b(t) = \frac{DRM_{t_a}}{(DRM^* - DRM_{t_e})} \quad (26)$$

The value of $b(t)$ is plotted as a function of t for fallout arrival times of two, five, ten, and twenty hours after detonation in Figure 36. The correction term applies to the Δt values of Figures 22 through 31.

Figure 1
FALLOUT DECAY CURVE

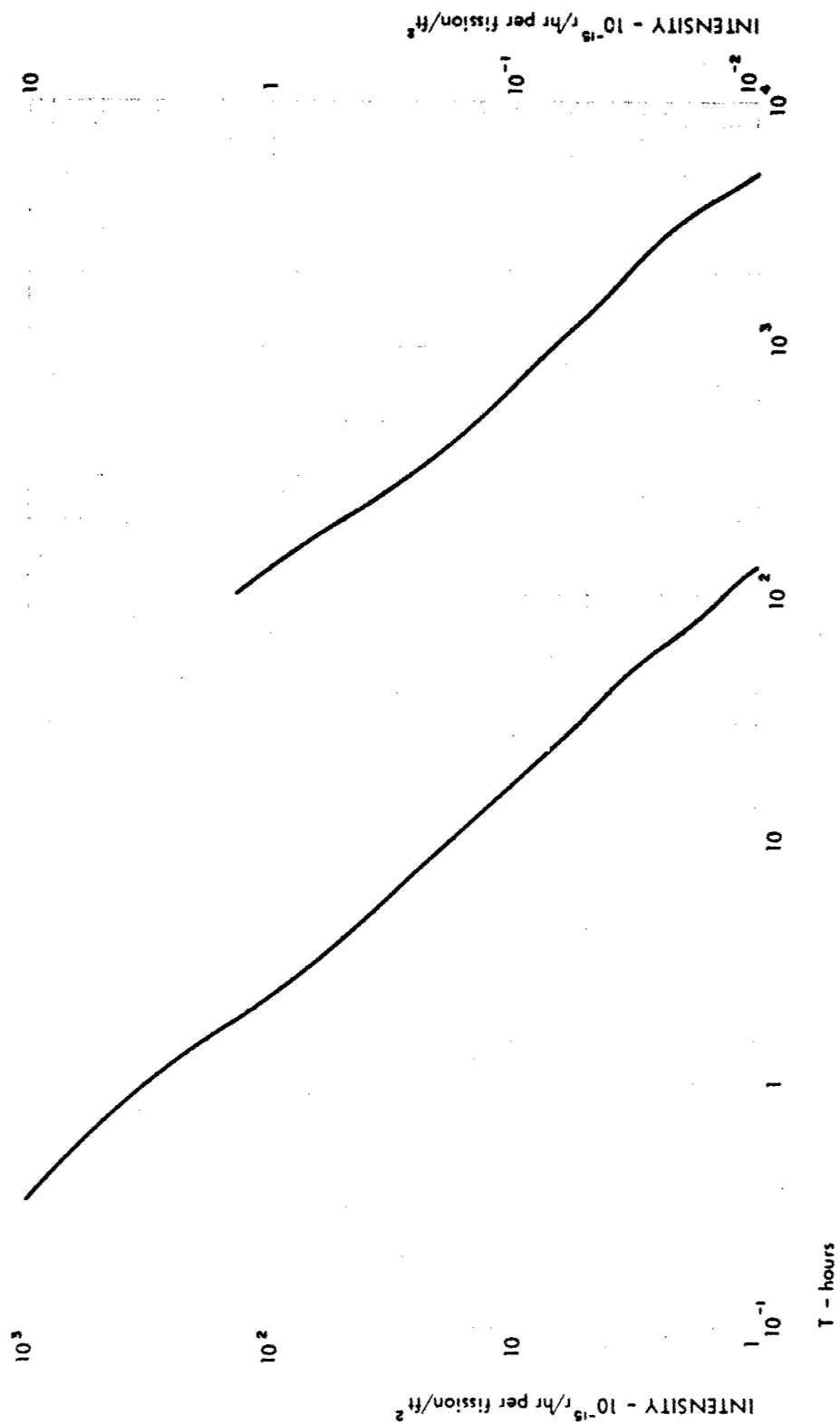


Figure 2

DOSE-RATE MULTIPLIER CURVES

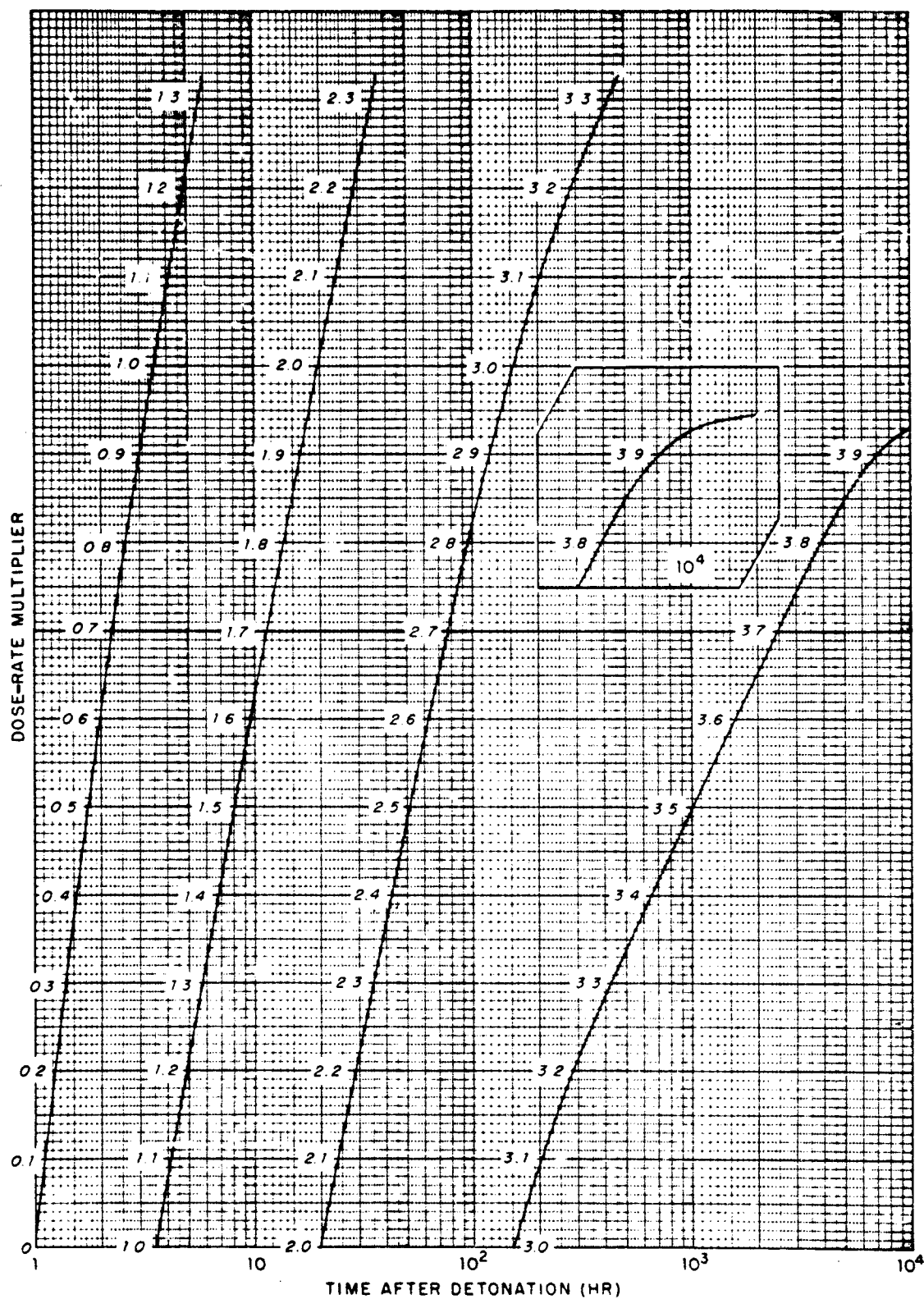


Figure 3
EXPOSURE-DOSE CRITERIA OF THREE RADIATION INJURY CATEGORIES
FOR HUMANS

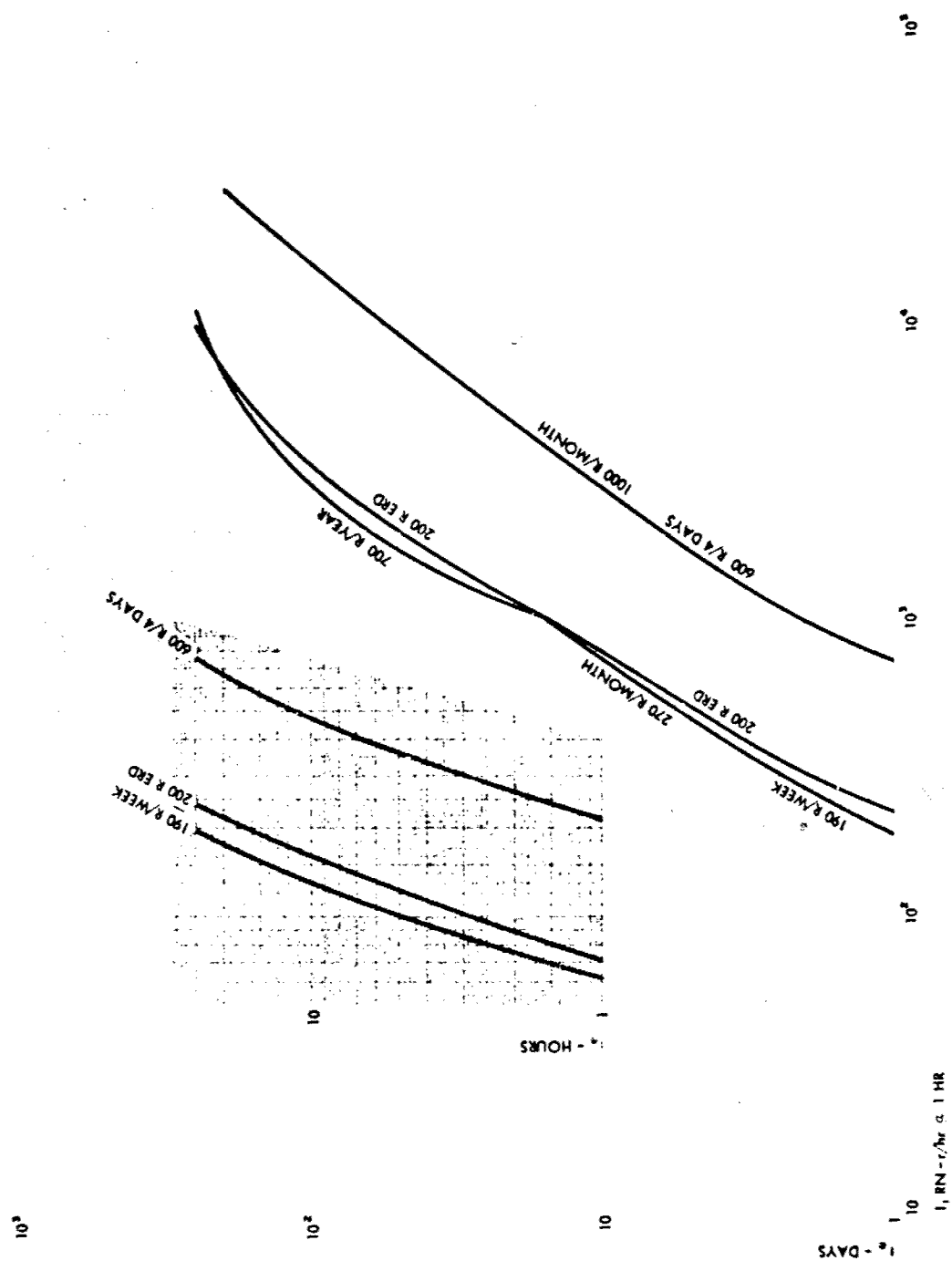


Figure 4
 MAXIMUM VALUES OF RN_3 FOR VARIOUS VALUES OF RN_1 AND
 I_s WITH A SHELTER-STAY TIME OF ONE DAY

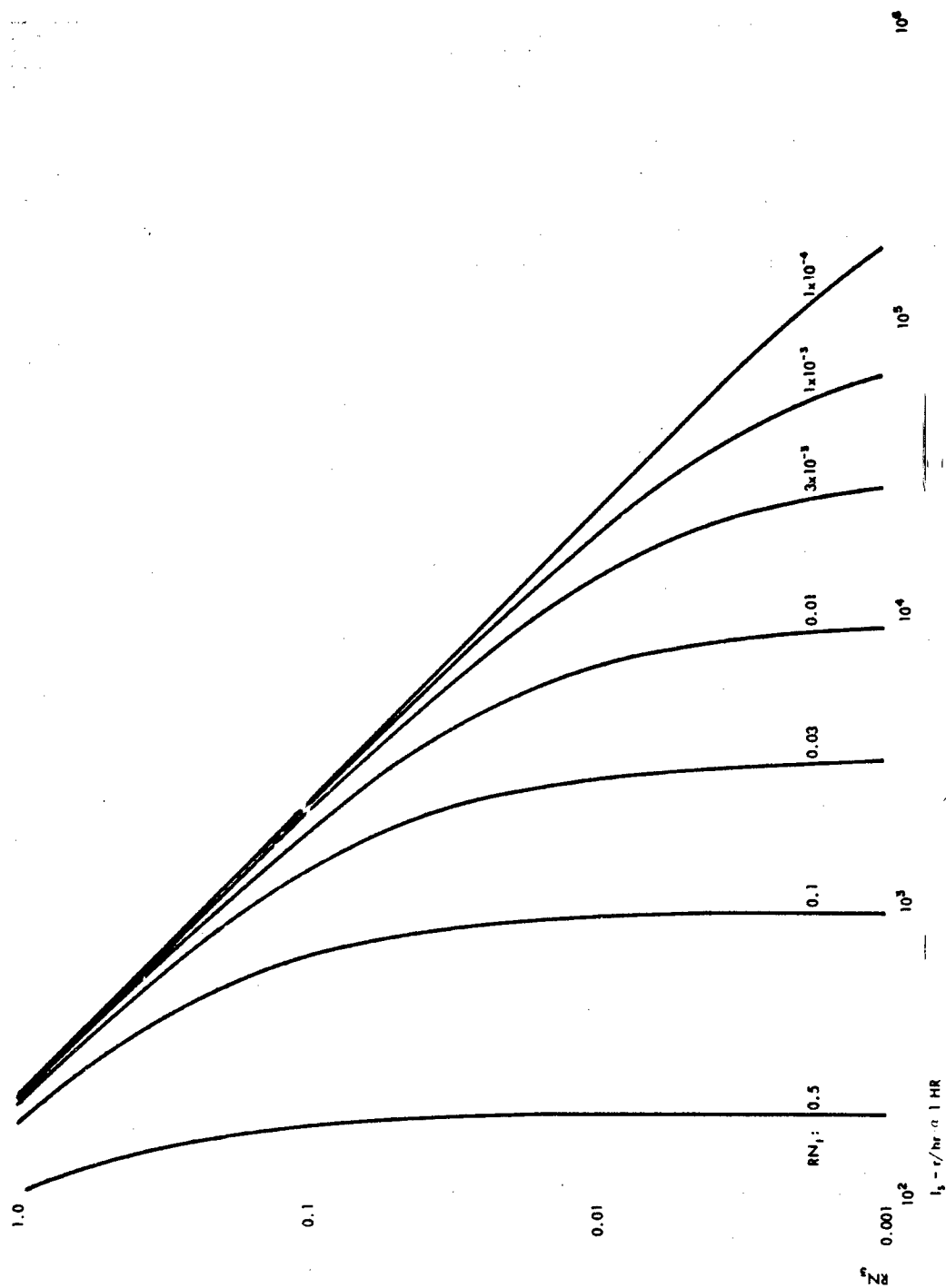


Figure 5

MAXIMUM VALUES OF RN_3 FOR VARIOUS VALUES OF RN_1 AND I_5 WITH A SHELTER-STAY TIME OF THREE AND A HALF DAYS

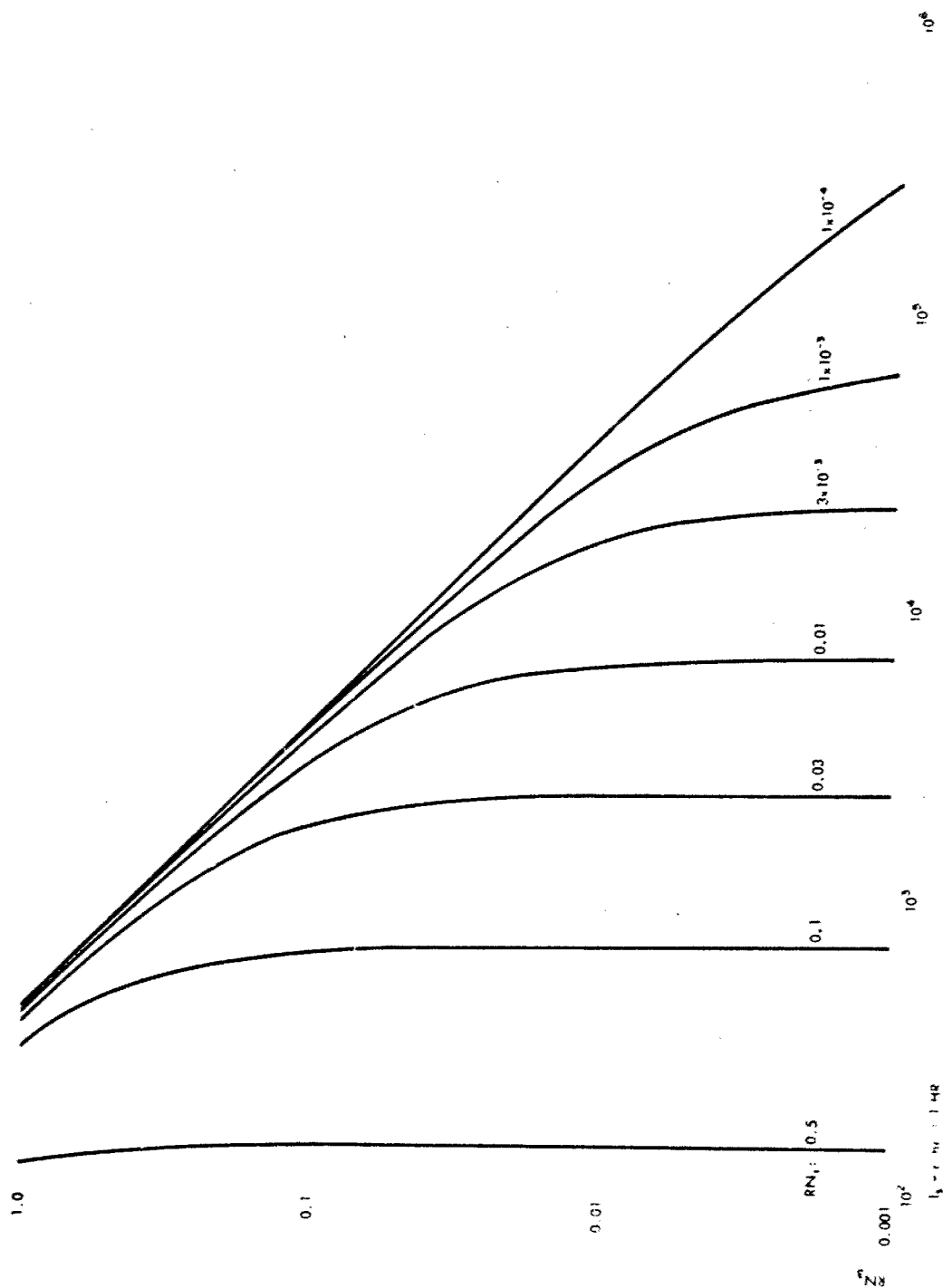


Figure 6.
MAXIMUM VALUES OF RN_3 FOR VARIOUS VALUES OF RN_1 AND
 I_s WITH A SHELTER-STAY TIME OF ONE WEEK

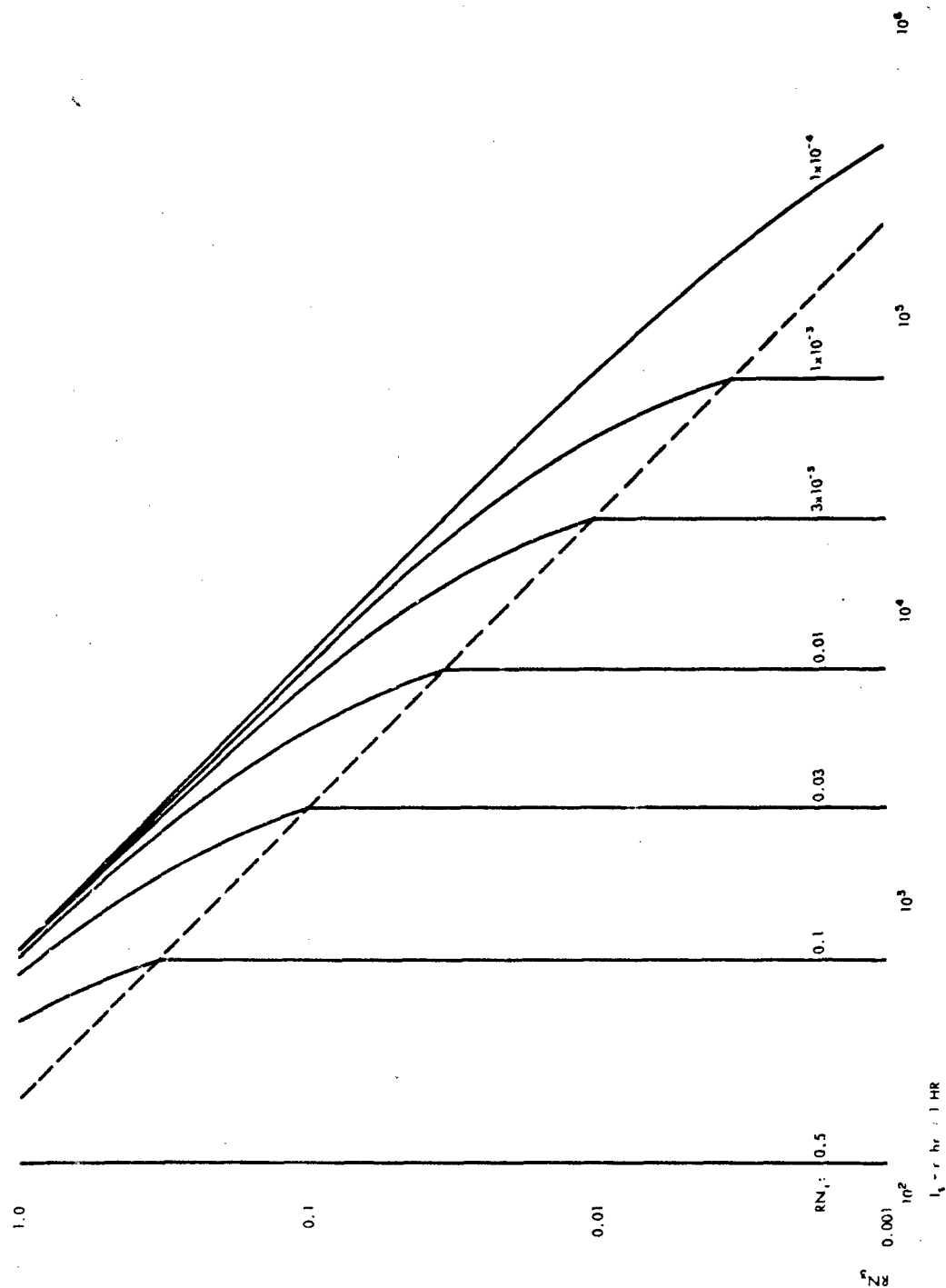


Figure 7

MAXIMUM VALUES OF RN_3 FOR VARIOUS VALUES OF RN_1 AND I_s WITH A SHELTER-STAY TIME OF TWO WEEKS

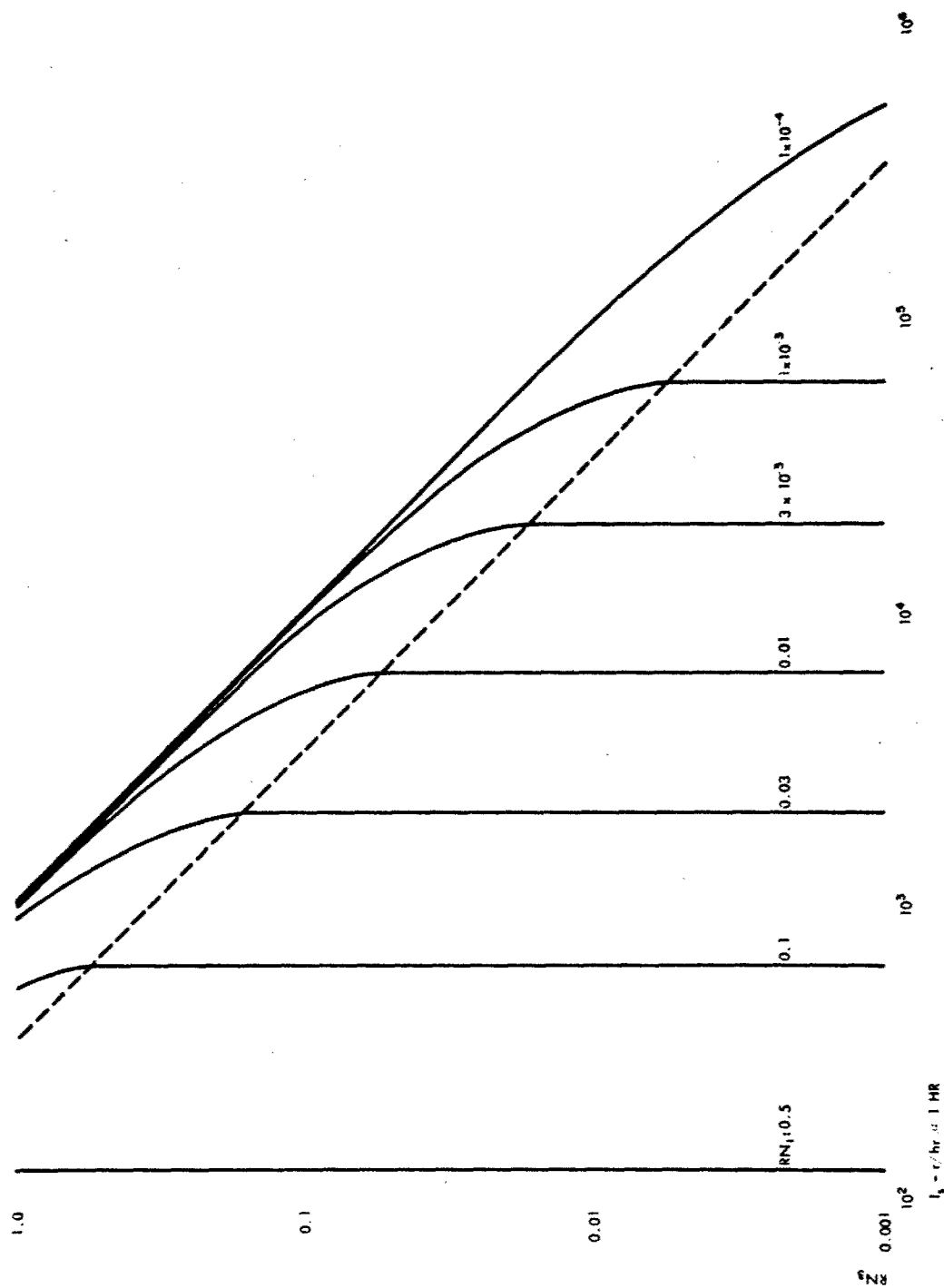


Figure 8

MAXIMUM VALUES OF RN_3 FOR VARIOUS VALUES OF RN_1 AND I_s WITH A SHELTER-STAY TIME OF ONE MONTH

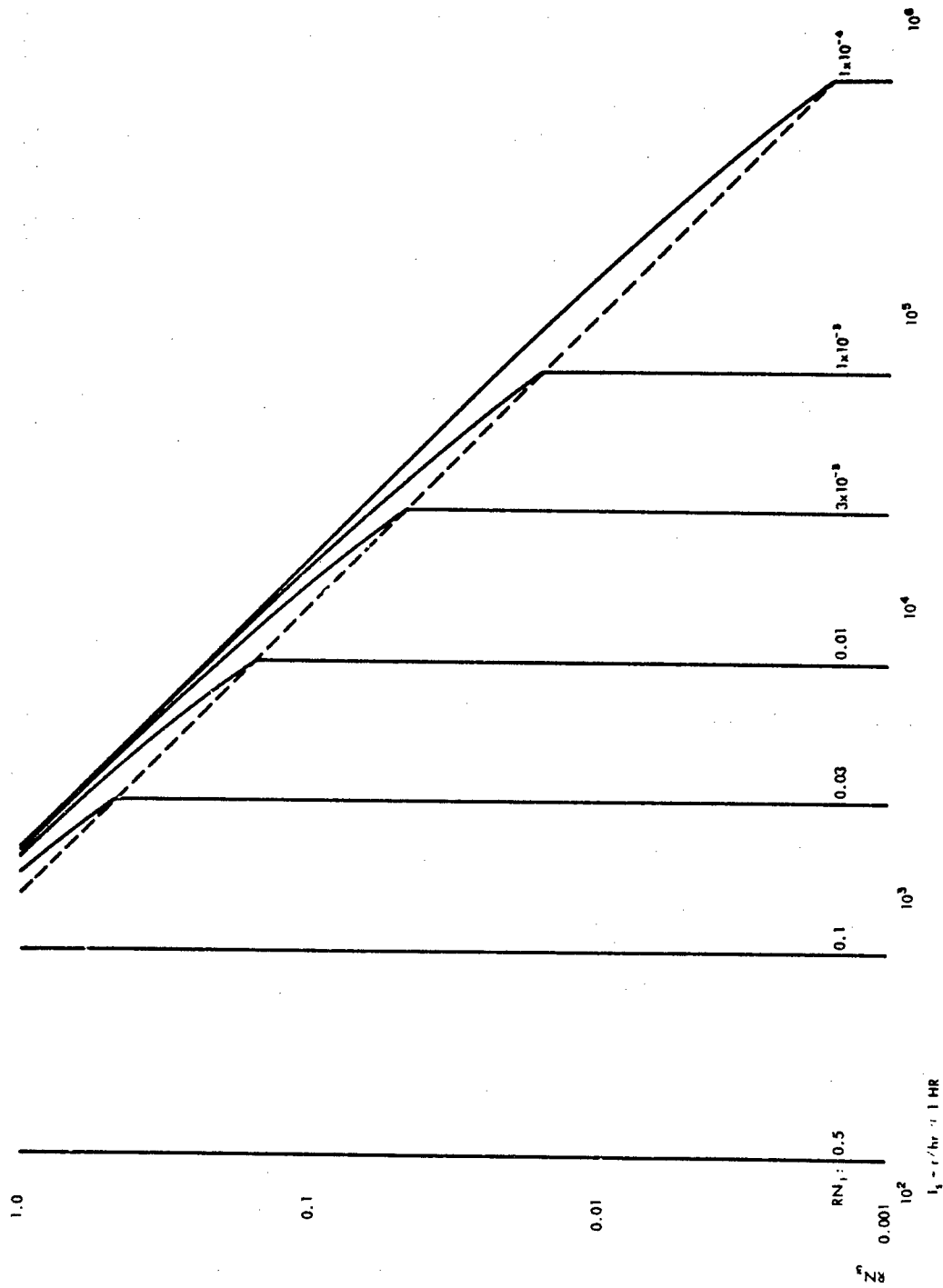


Figure 9

MAXIMUM VALUES OF RN_1 FOR VARIOUS VALUES OF RN_3 AND I_s WITH A SHELTER-STAY TIME OF ONE DAY

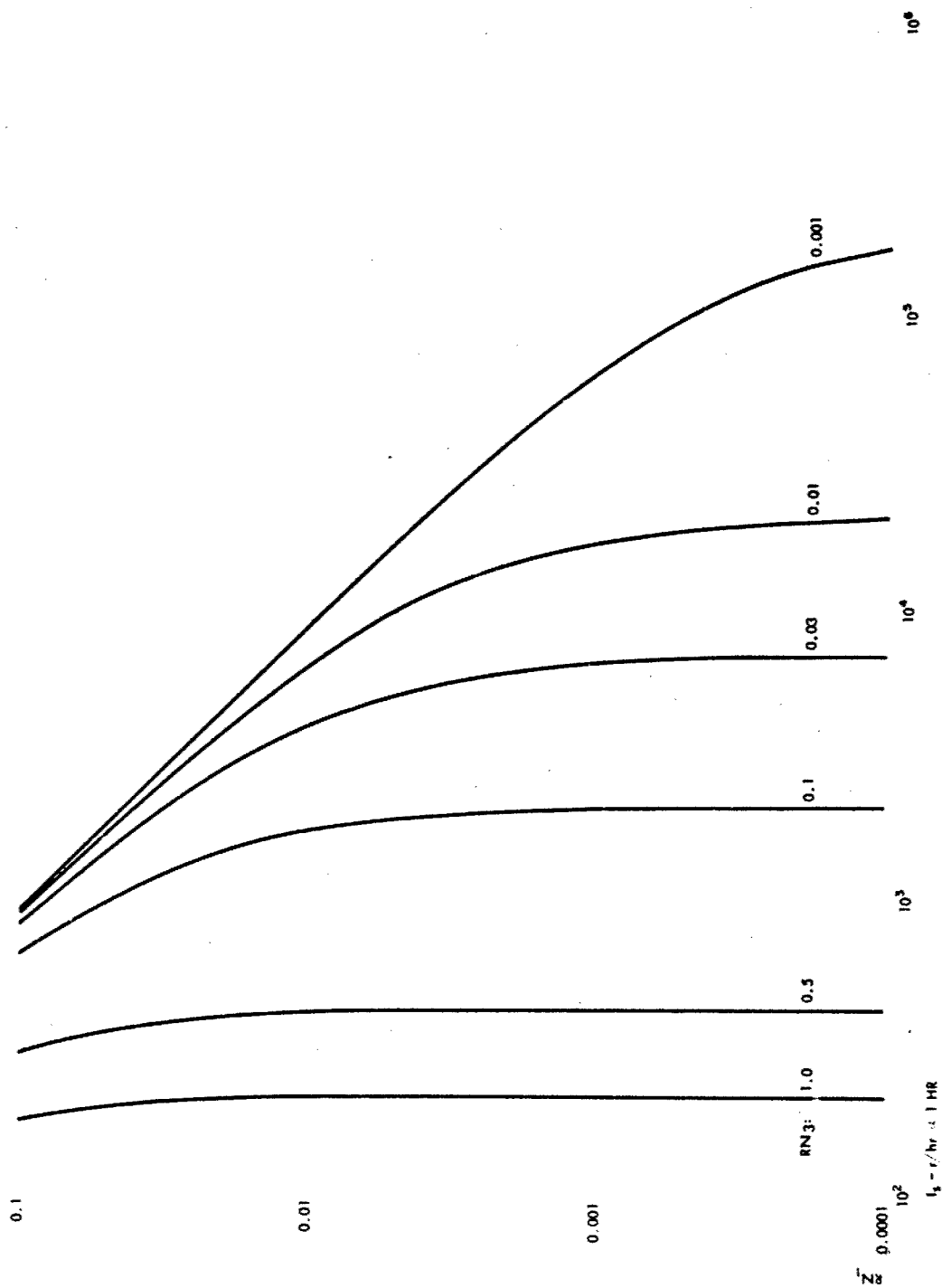


Figure 10
 MAXIMUM VALUES OF RN_1 FOR VARIOUS VALUES OF RN_3 AND
 I_s WITH A SHELTER-STAY TIME OF THREE AND A HALF DAYS

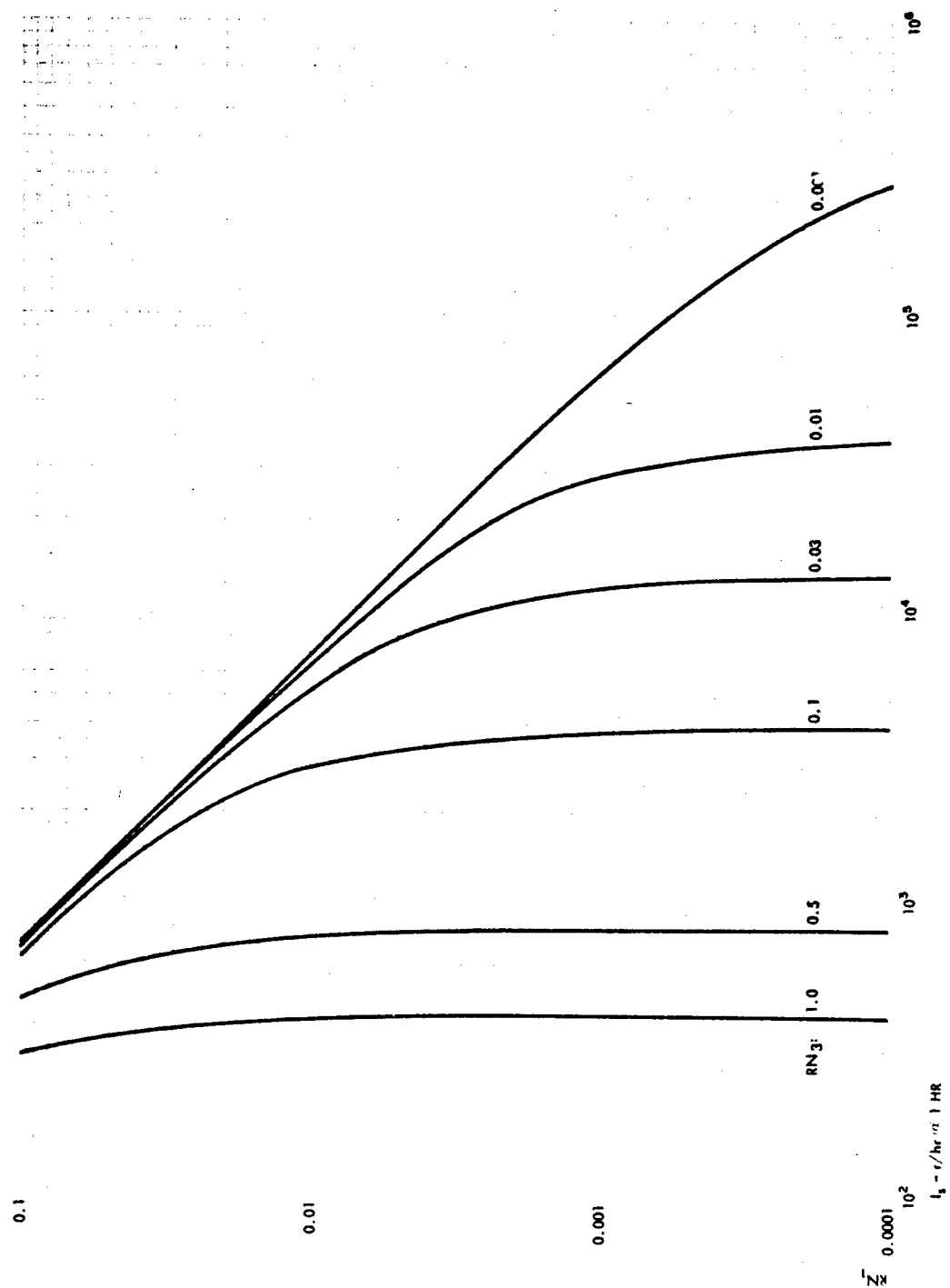


Figure 11

MAXIMUM VALUES OF RN_1 FOR VARIOUS VALUES OF RN_3 AND I_s WITH A SHELTER-STAY TIME OF ONE WEEK

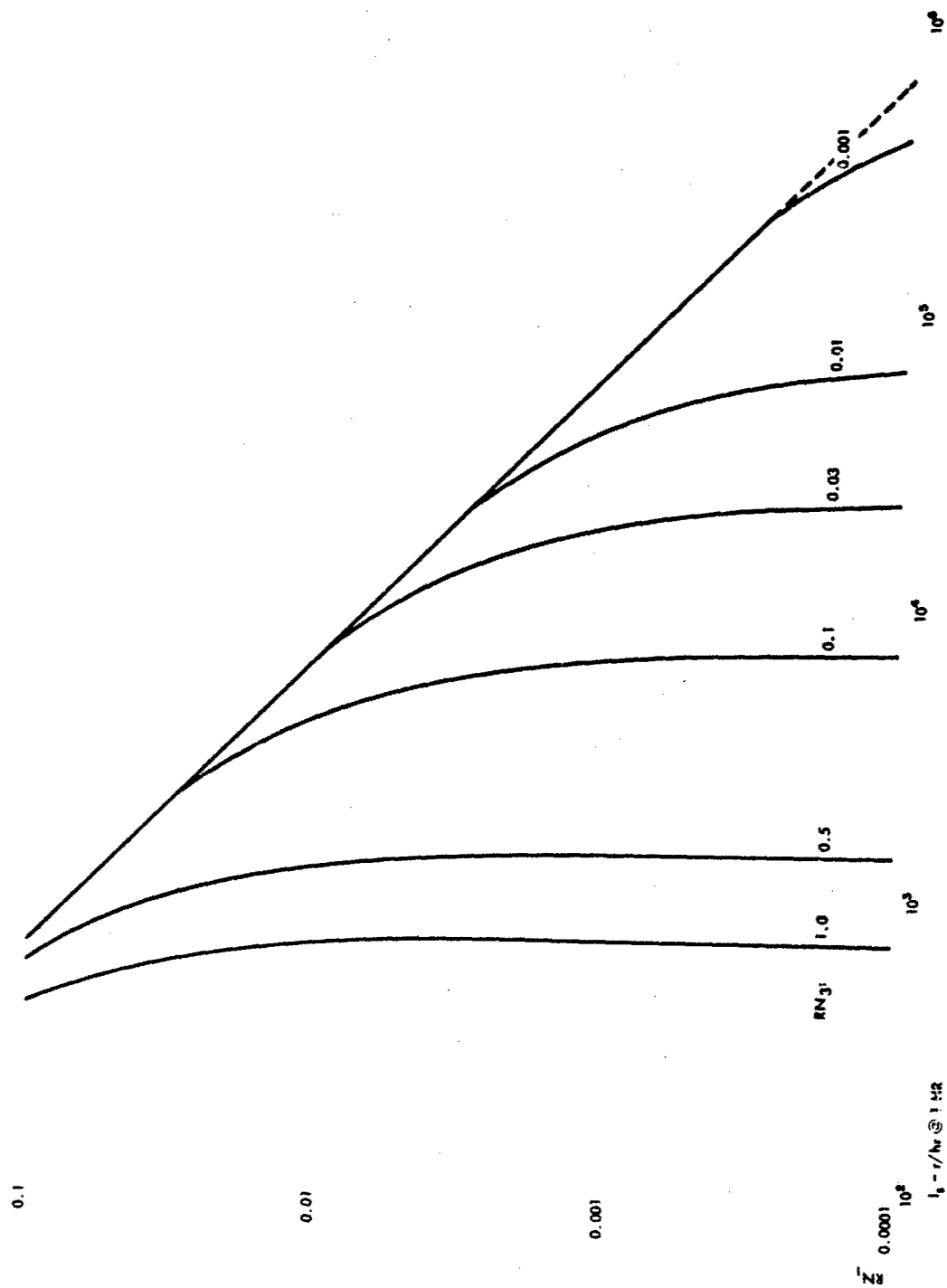


Figure 12

MAXIMUM VALUES OF RN_1 FOR VARIOUS VALUES OF RN_3 AND I_s WITH A SHELTER-STAY TIME OF TWO WEEKS

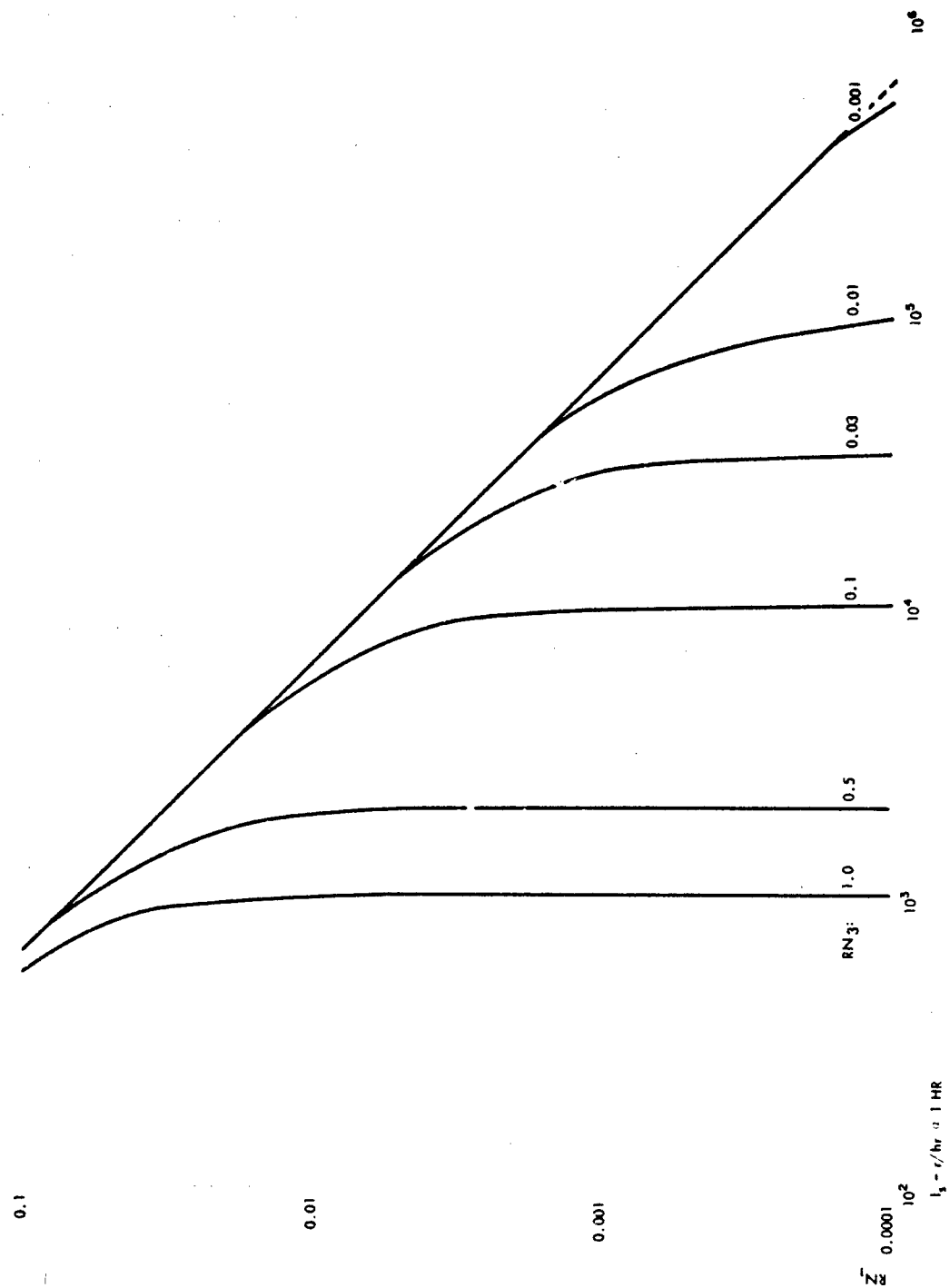


Figure 13

MAXIMUM VALUES OF RN_1 FOR VARIOUS VALUES OF RN_3 AND I_s WITH A SHELTER-STAY TIME OF ONE MONTH

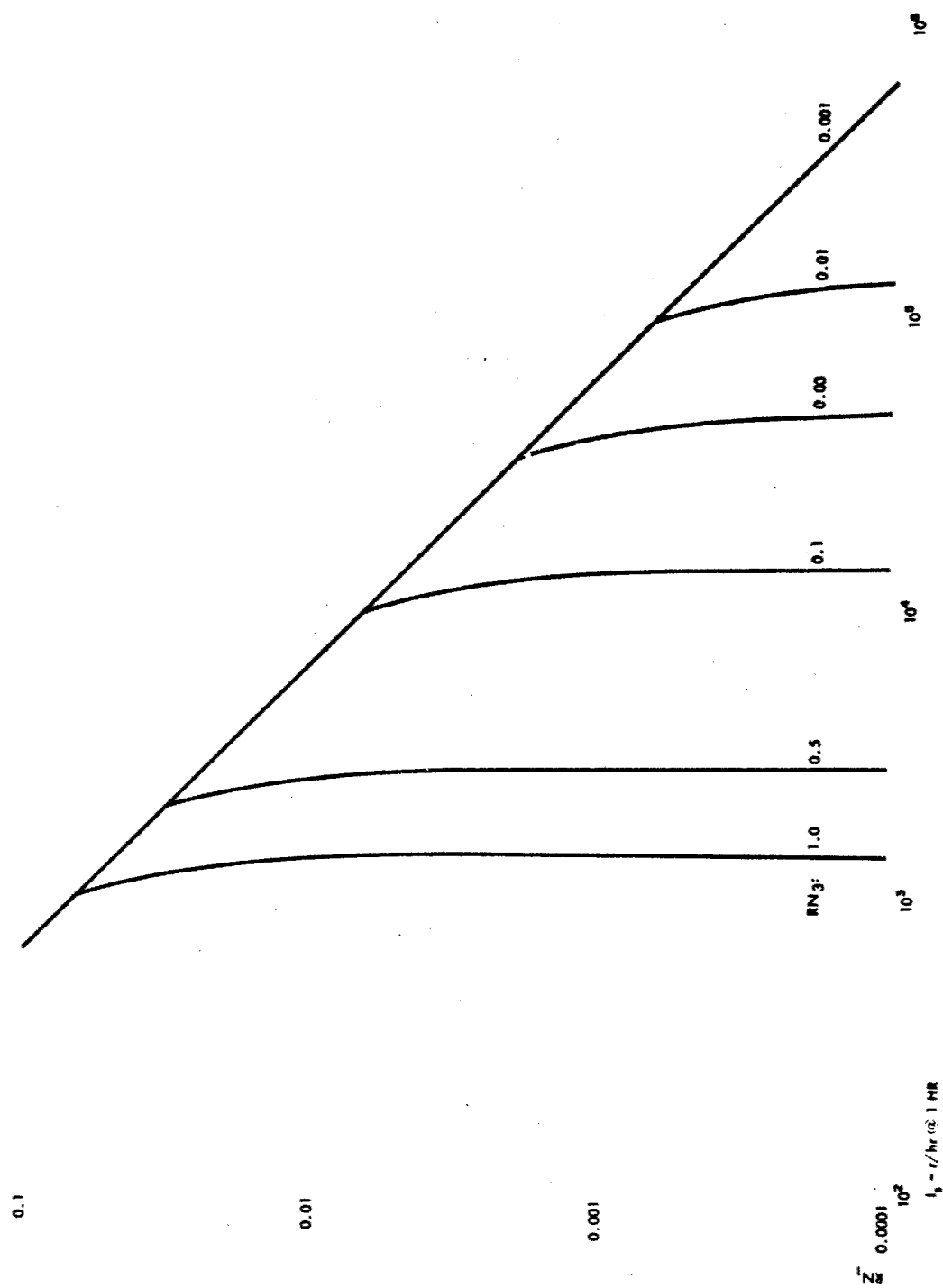


Figure 14

MINIMUM SHELTER-STAY TIMES (t_e) FOR VARIOUS
VALUES OF RN_3 AND I_s WITH $RN_1=0.1$

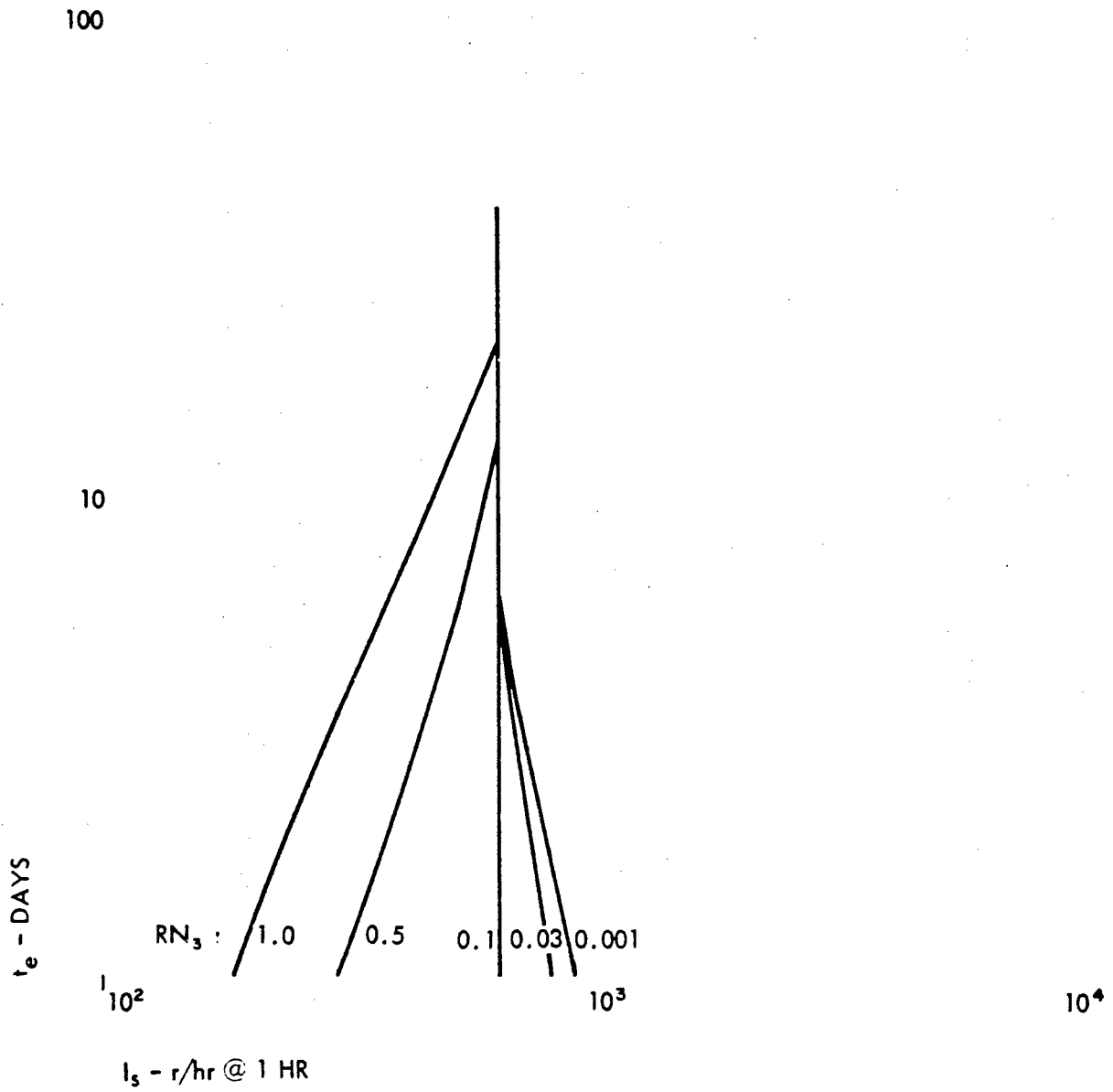


Figure 15

MINIMUM SHELTER-STAY TIMES (t_e) FOR VARIOUS
VALUES OF RN_3 AND I_3 WITH $RN_1=0.01$

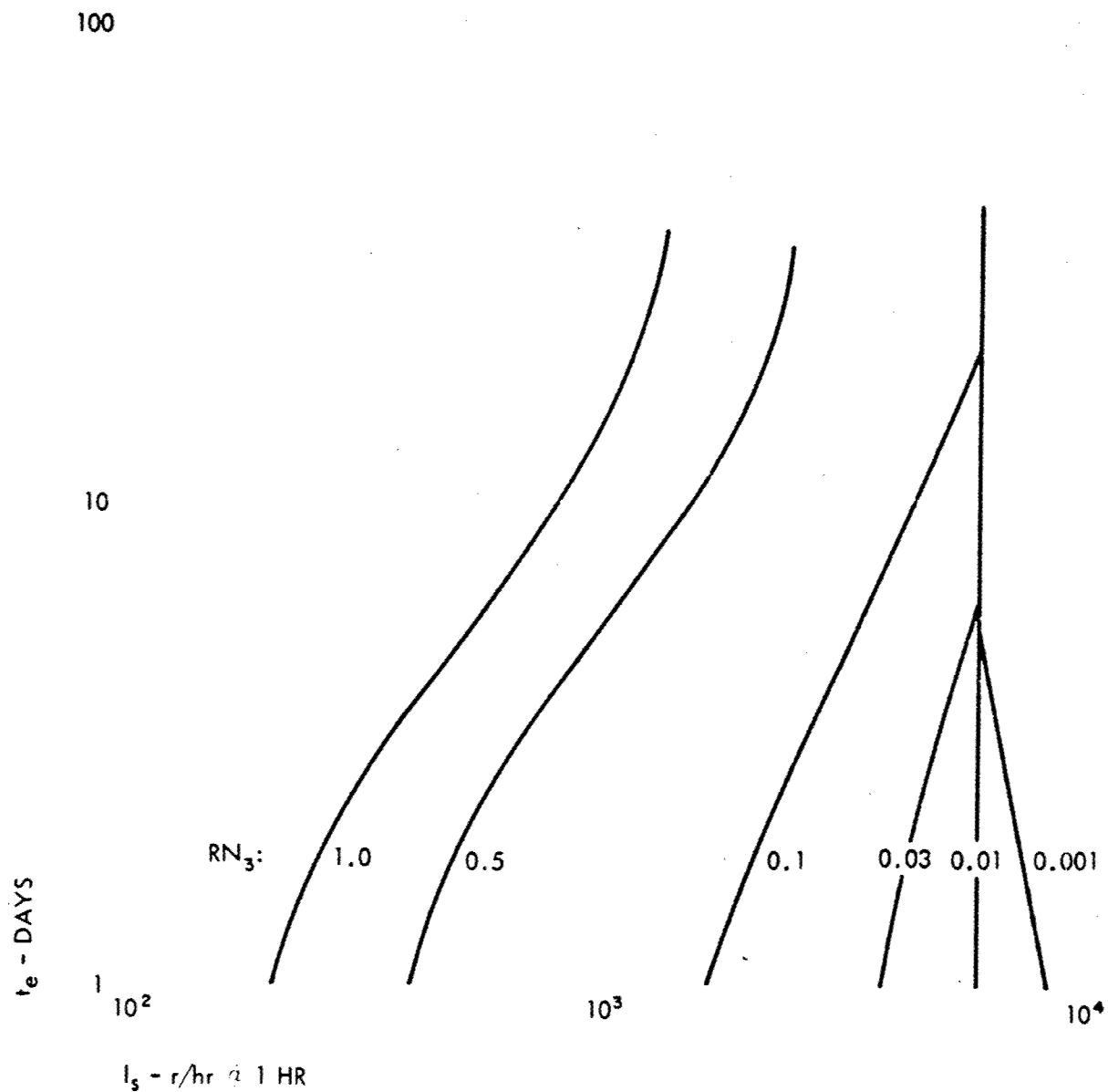


Figure 16

MINIMUM SHELTER-STAY TIMES (t_e) FOR VARIOUS VALUES OF RN_3 AND I_s WITH $RN_1 = 0.001$

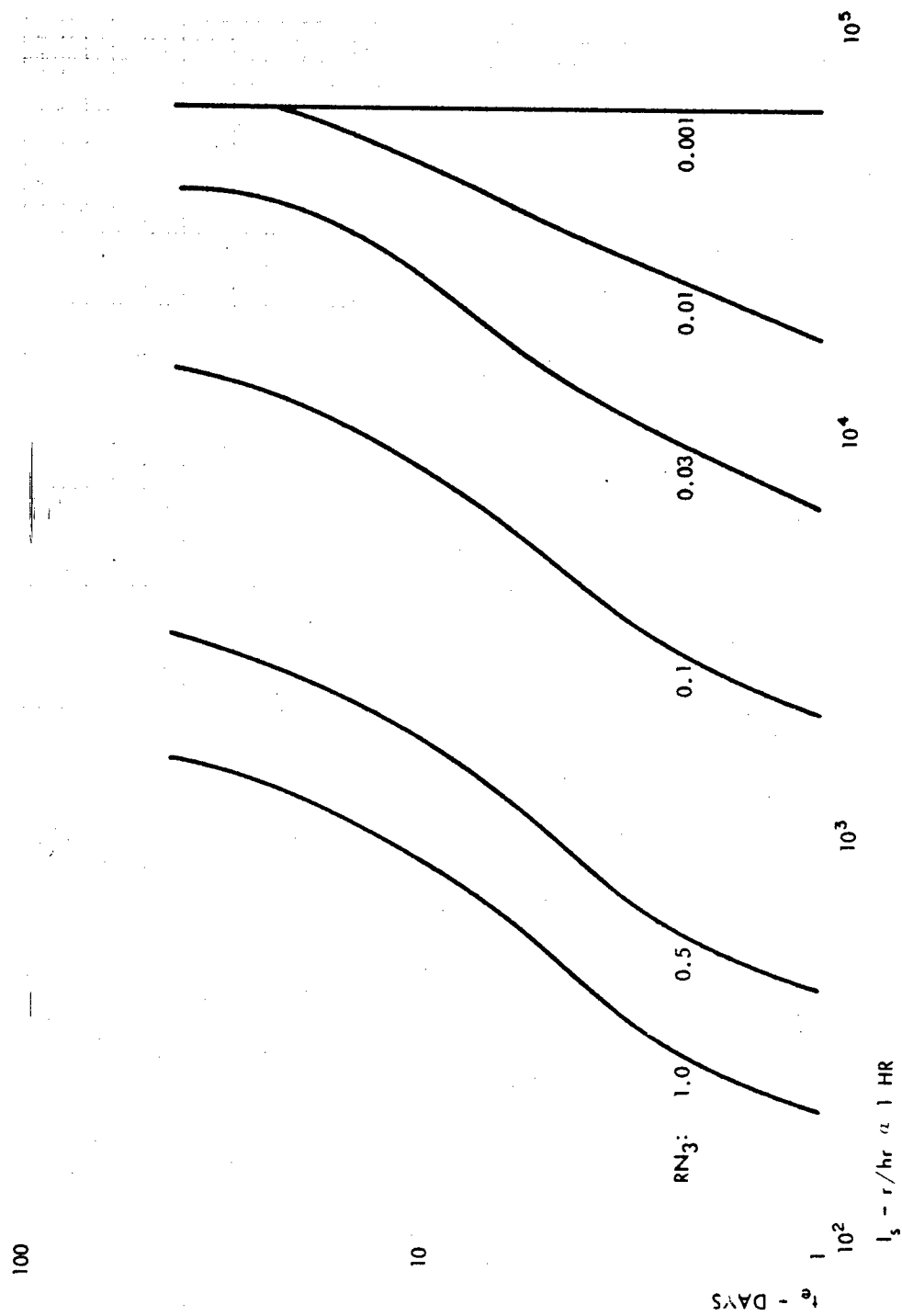


Figure 17

MINIMUM SHELTER-STAY TIMES (t_e) FOR VARIOUS VALUES OF RN_3 AND I_s
WITH $RN_1 = 0.0001$

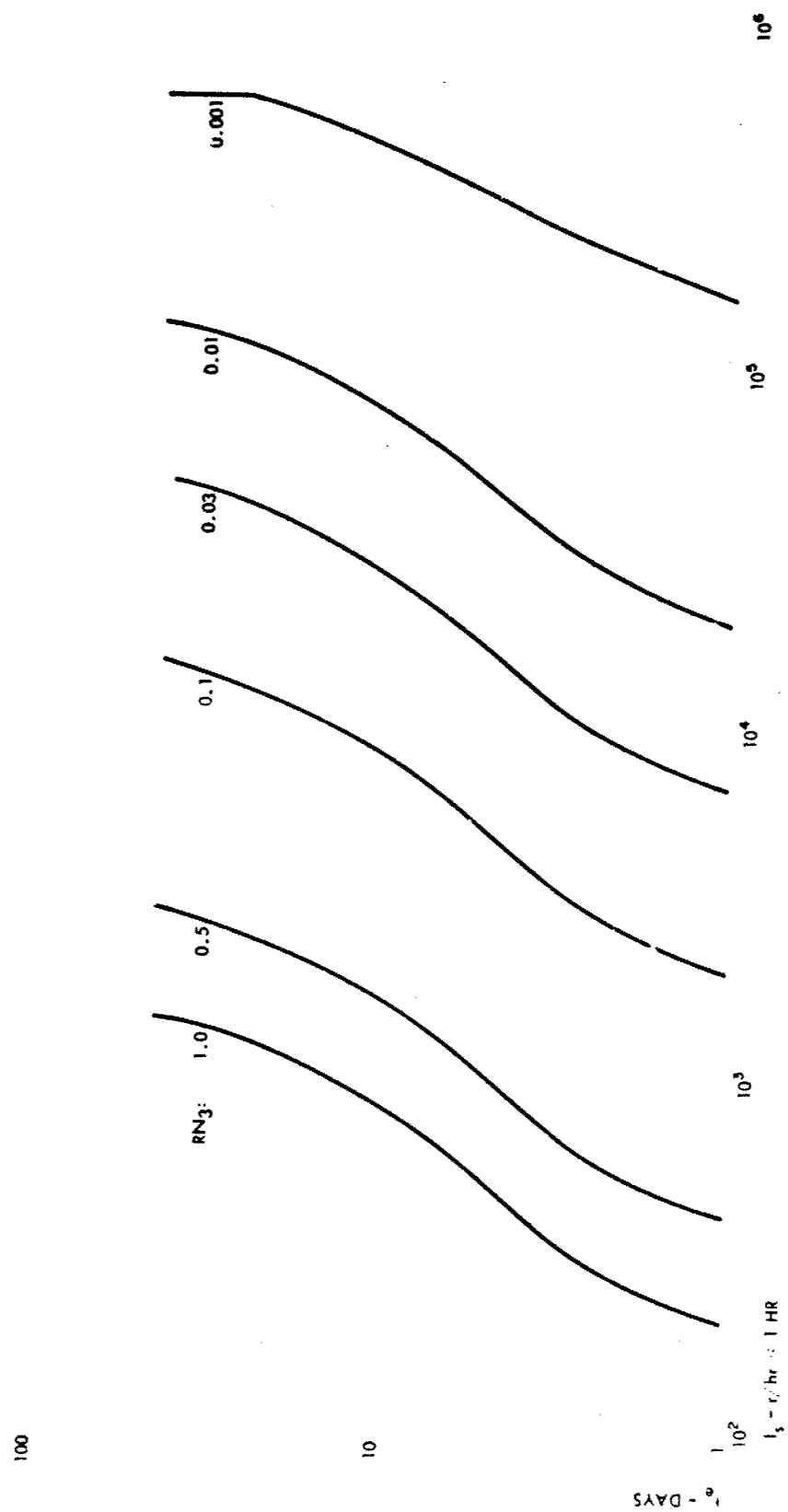


Figure 18

MINIMUM SHELTER-STAY TIMES (t_e) FOR VARIOUS VALUES
OF RN_1 AND I_s WITH $RN_3 = 1.0$

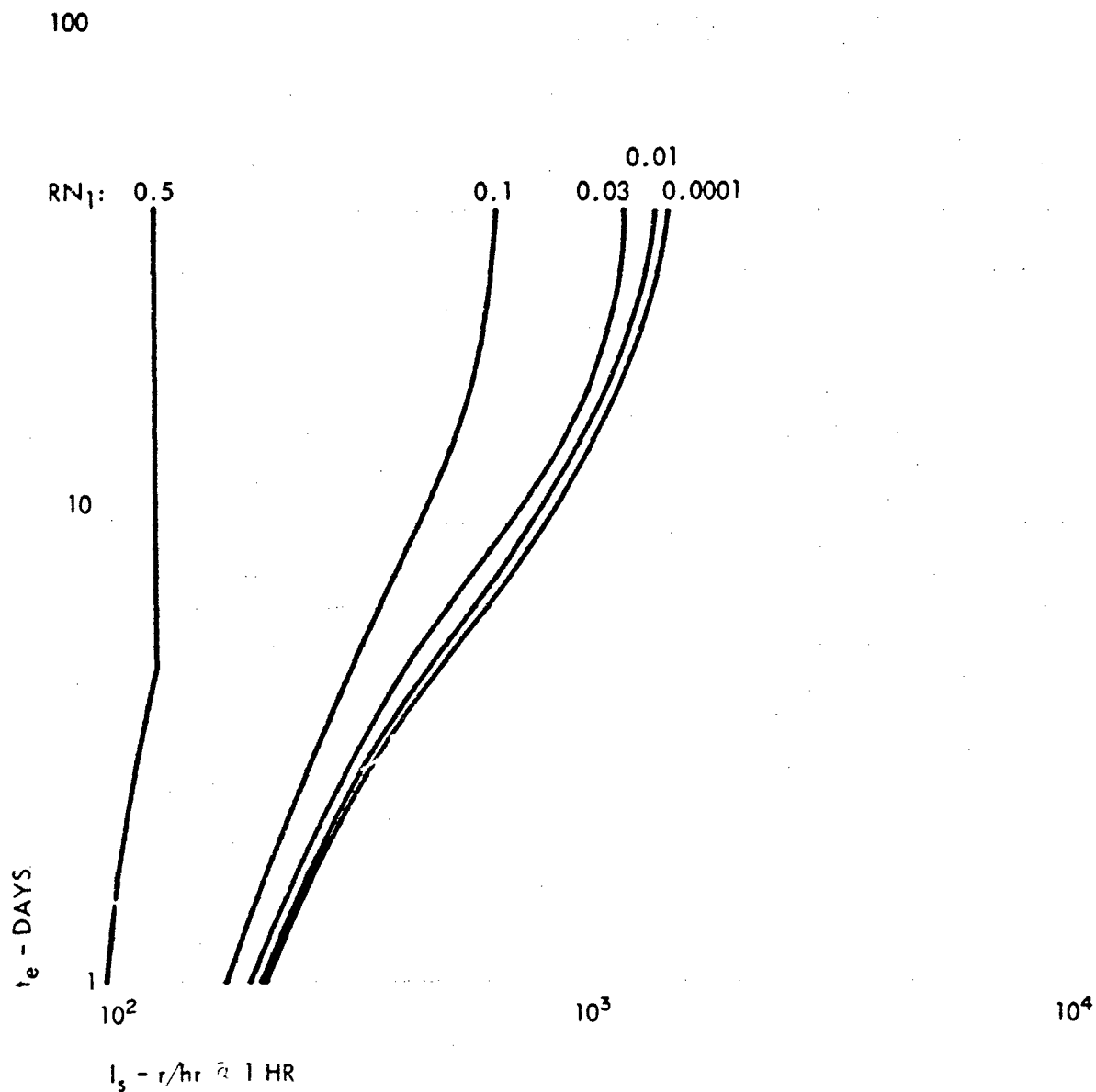


Figure 19

MINIMUM SHELTER-STAY TIMES (t_e) FOR VARIOUS
VALUES OF RN_1 AND I_s WITH $RN_3 = 0.5$

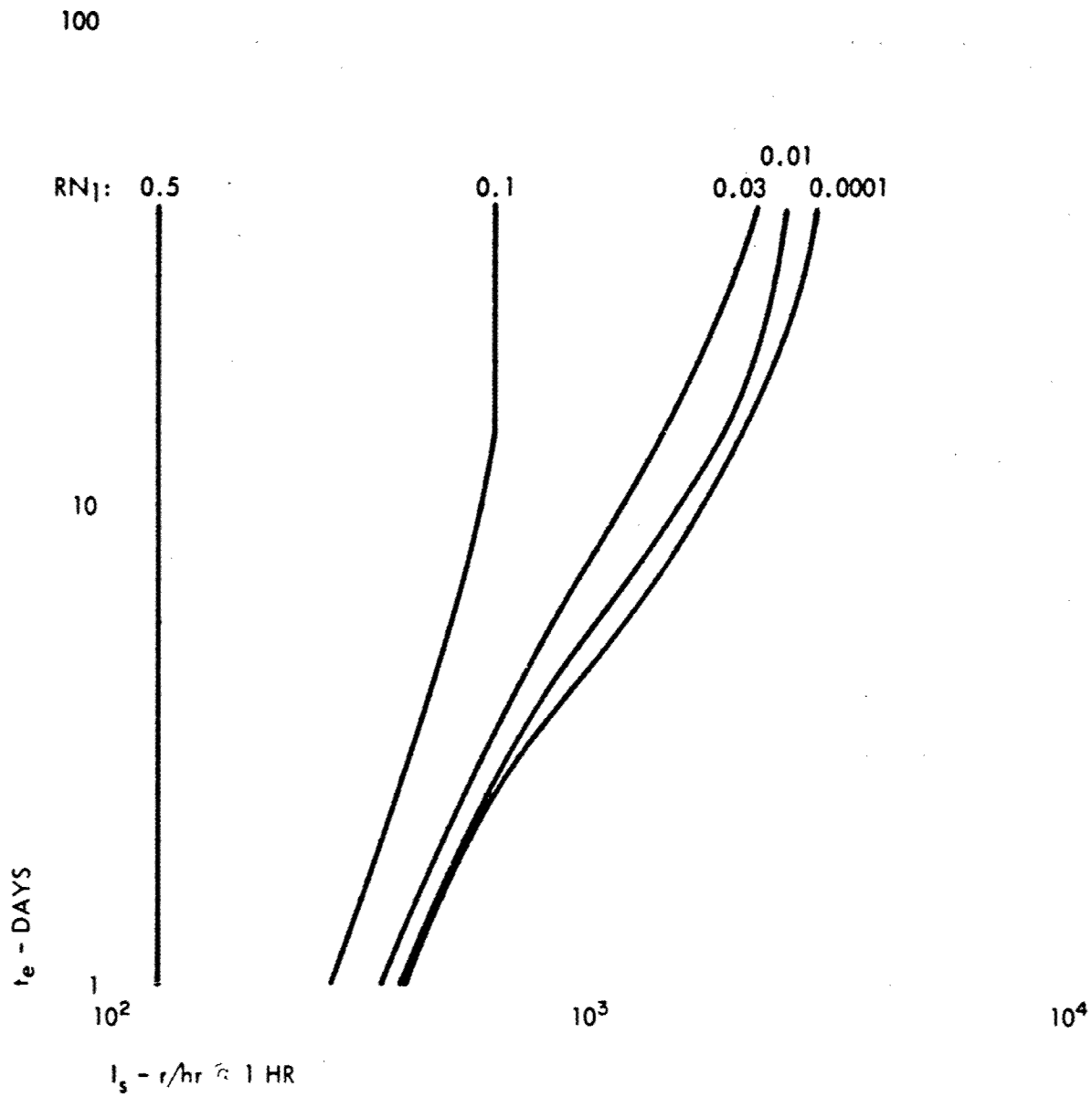


Figure 20

MINIMUM SHELTER-STAY TIMES (t_e) FOR VARIOUS VALUES OF RN_1
AND I_s WITH $RN_3 = 0.1$

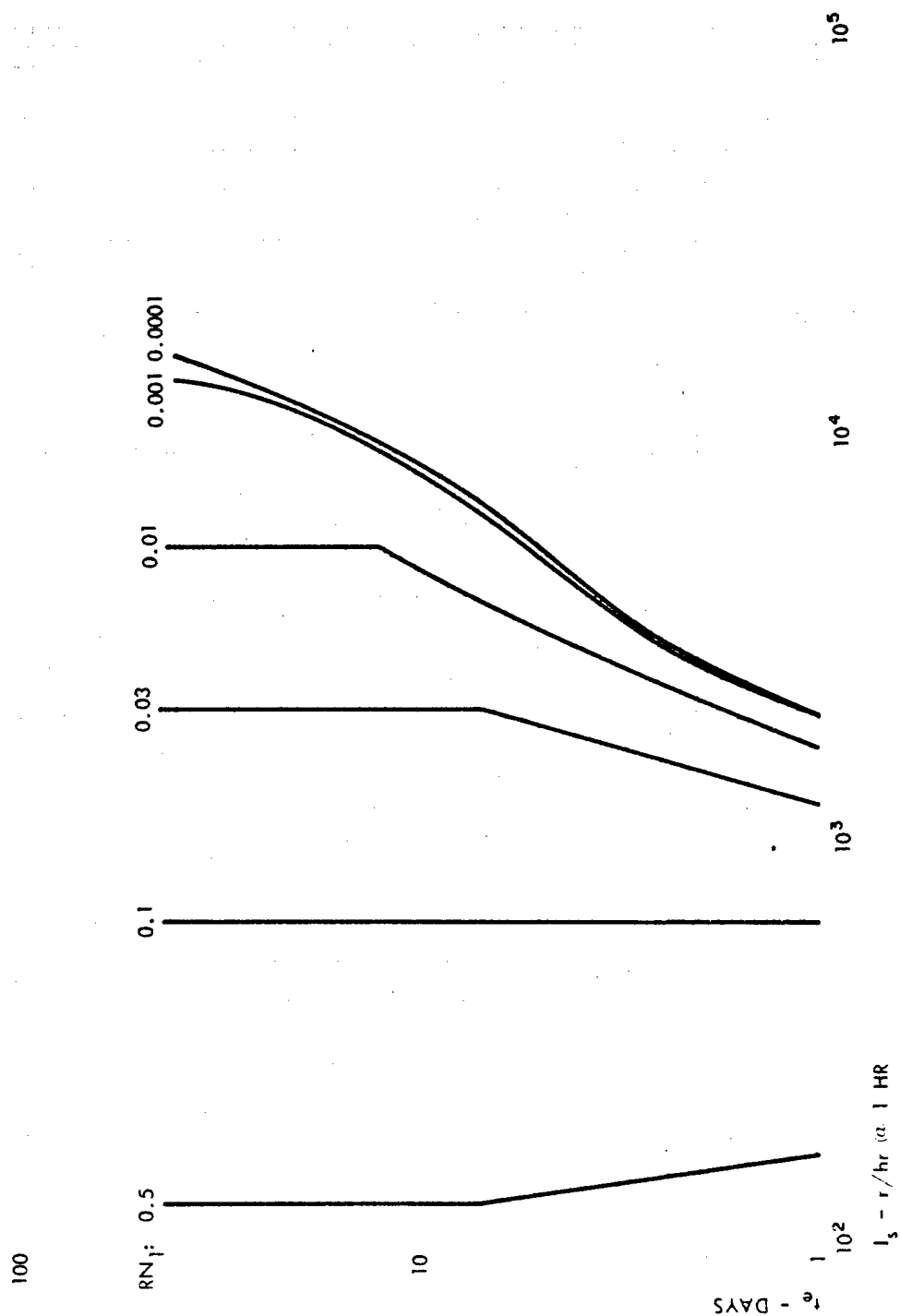


Figure 21

MINIMUM SHELTER-STAY TIMES (t_e) FOR VARIOUS VALUES OF RN_1 AND I_s
WITH $RN_3 = 0.01$

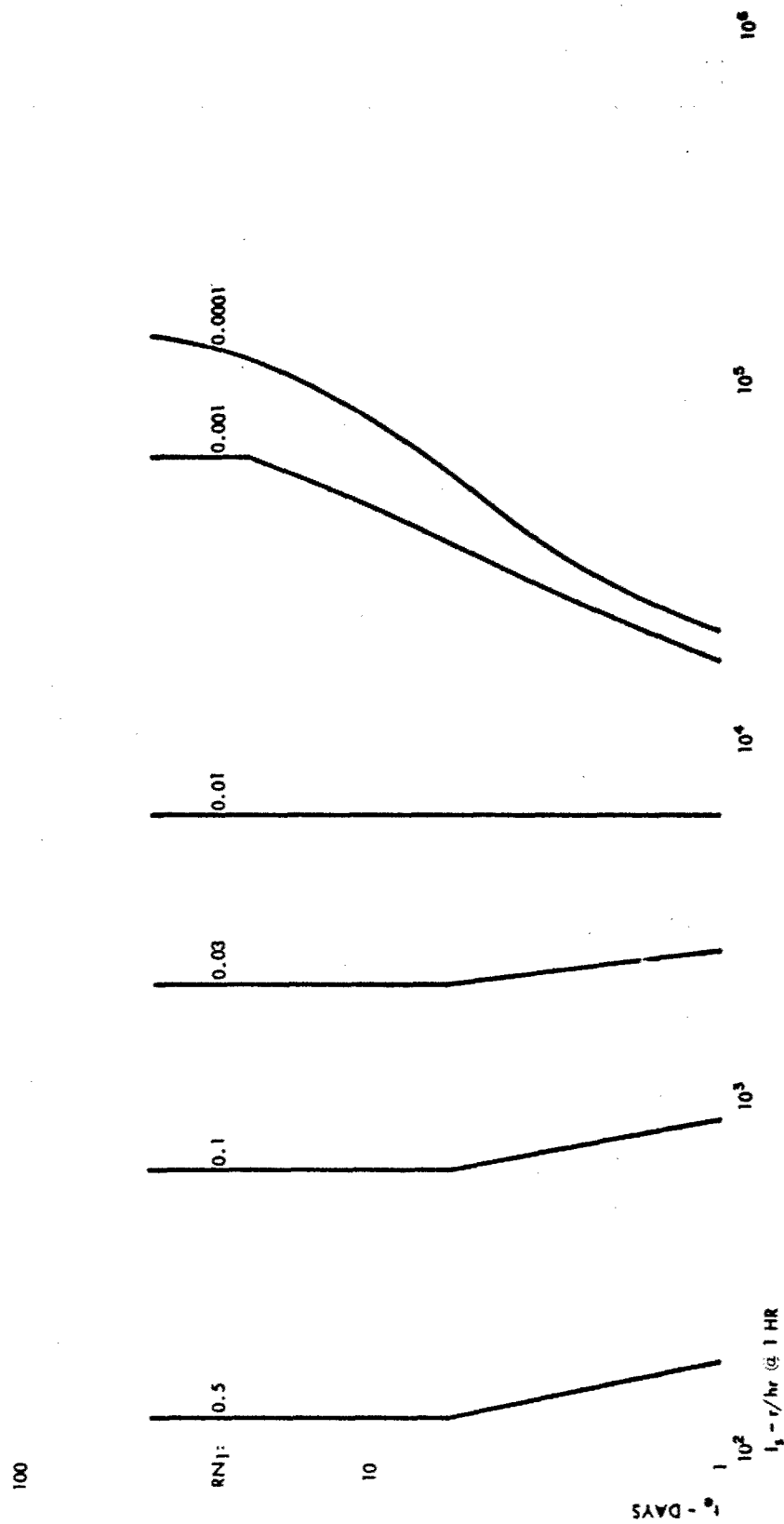


Figure 22

MAXIMUM TIMES ALLOWED FOR EVACUATION OR DECONTAMINATION
STARTING AT ONE DAY AFTER ATTACK FROM SHELTERS WITH
SELECTED RN_1 VALUES

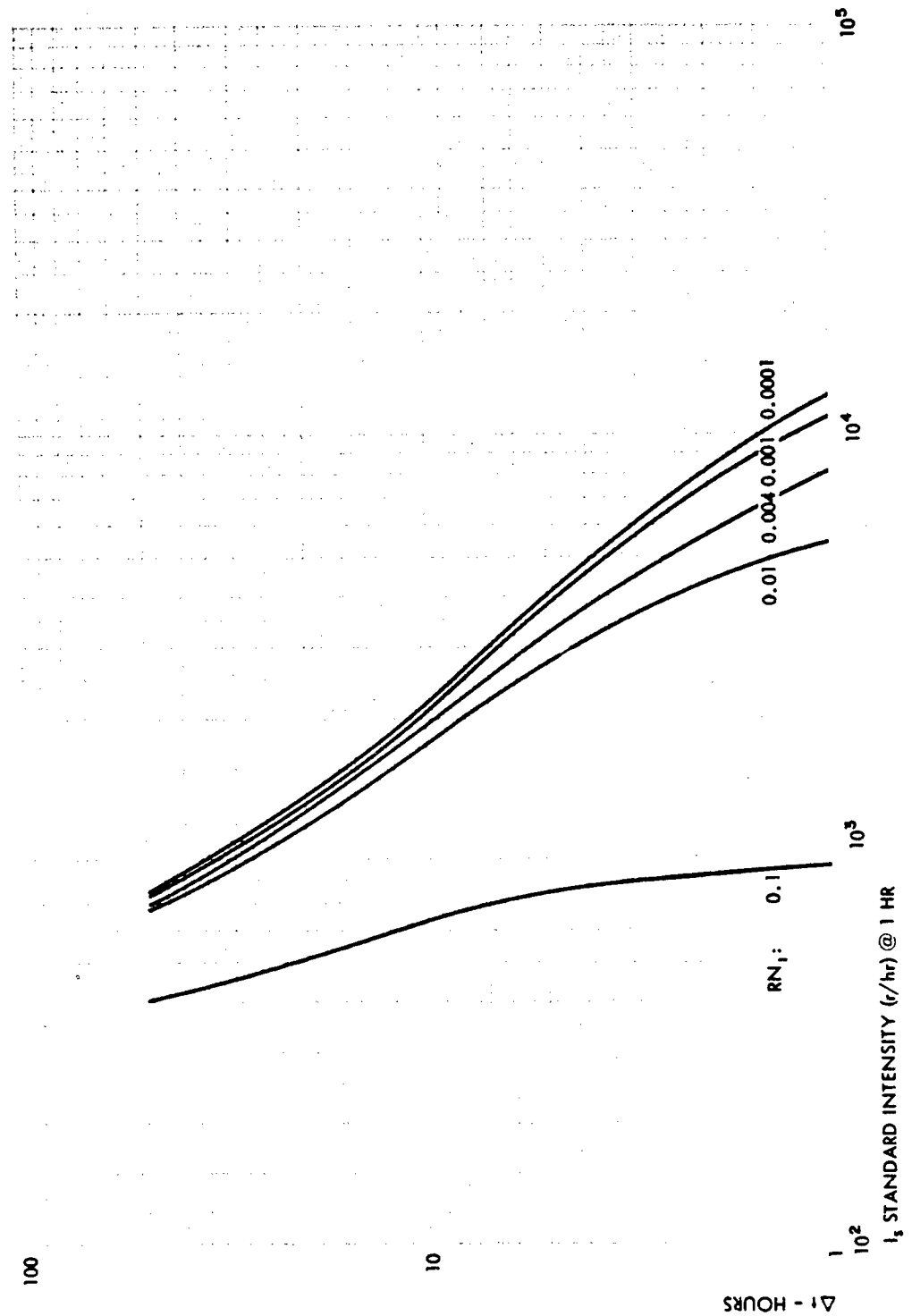


Figure 23

MAXIMUM TIMES ALLOWED FOR EVACUATION OR DECONTAMINATION
STARTING AT TWO DAYS AFTER ATTACK FROM SHELTERS WITH
SELECTED RN_1 VALUES

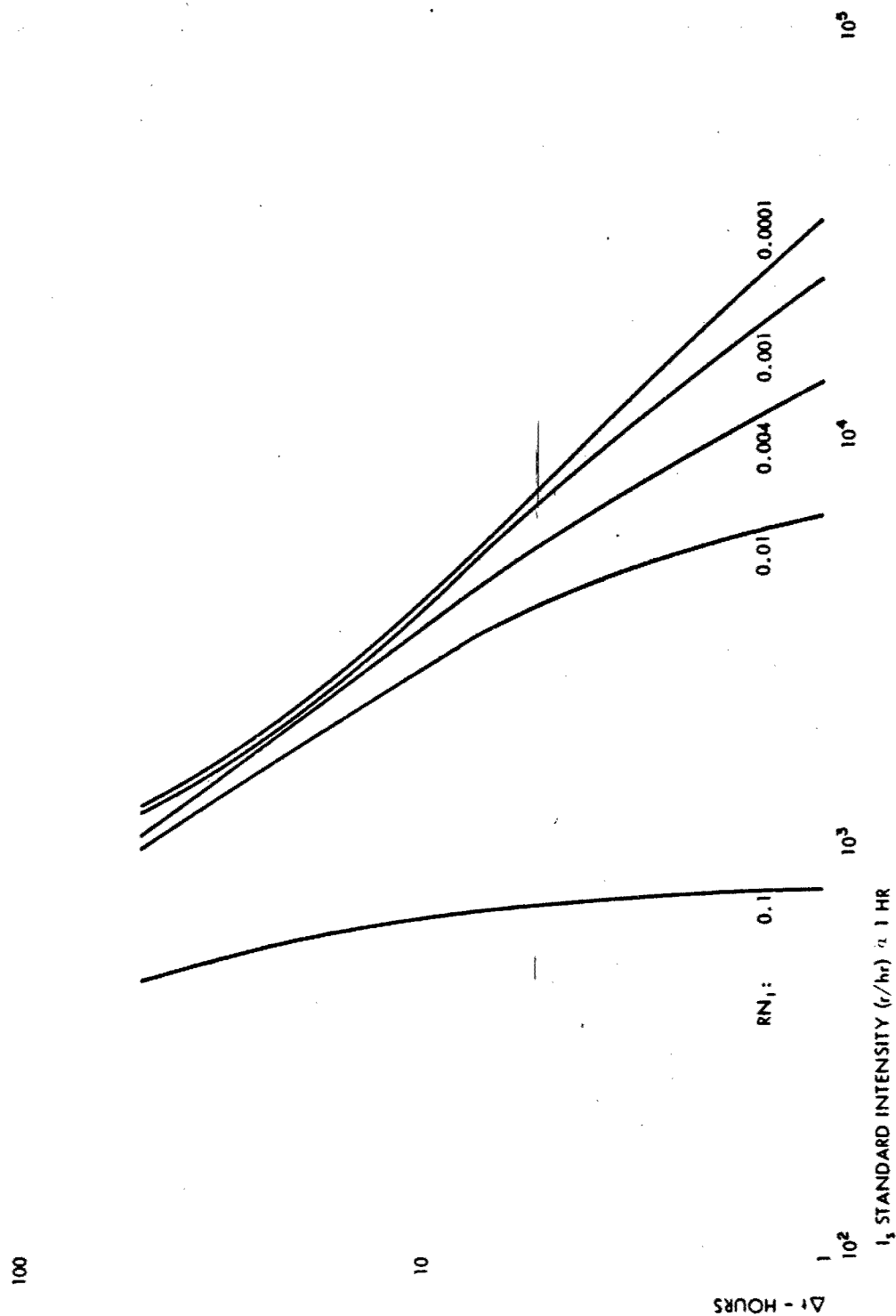


Figure 24

MAXIMUM TIMES ALLOWED FOR EVACUATION OR DECONTAMINATION
STARTING AT FOUR DAYS AFTER ATTACK FROM SHELTERS WITH
SELECTED RN_1 VALUES

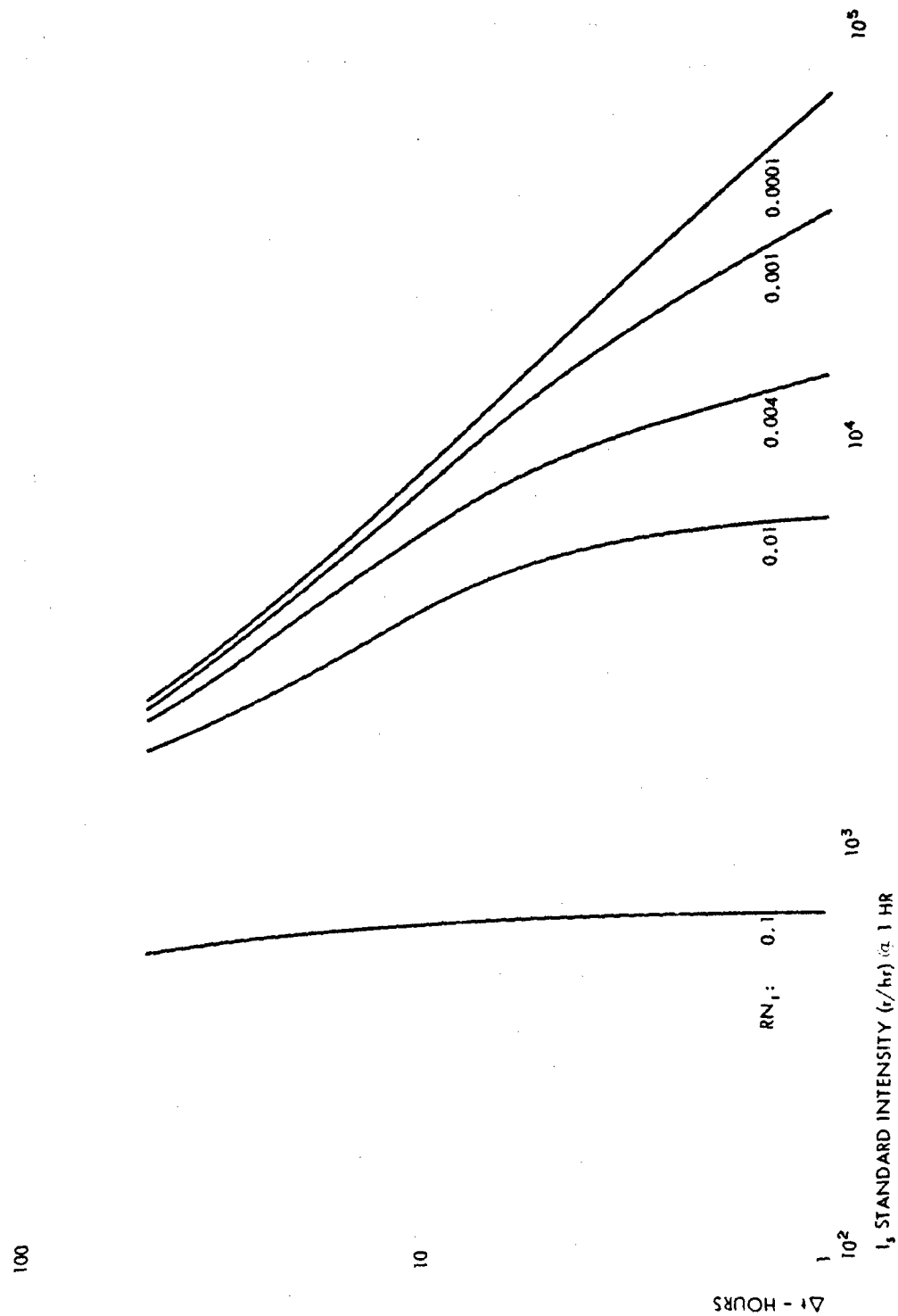


Figure 25

MAXIMUM TIMES ALLOWED FOR EVACUATION OR DECONTAMINATION
STARTING AT SEVEN DAYS AFTER ATTACK FROM SHELTERS WITH
SELECTED RN_1 VALUES

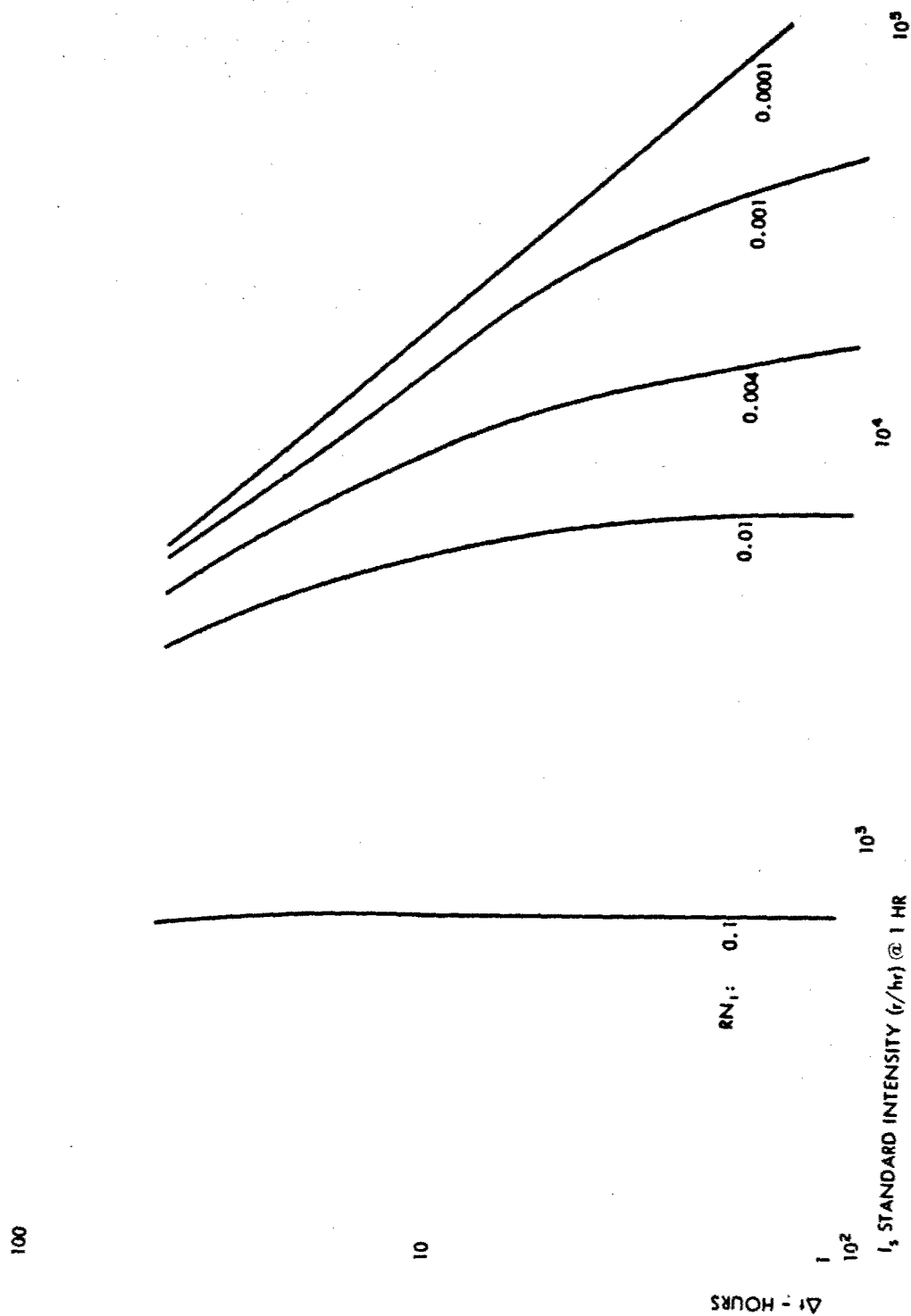


Figure 26

MAXIMUM TIMES ALLOWED FOR EVACUATION OR DECONTAMINATION
STARTING AT FOURTEEN DAYS AFTER ATTACK FROM SHELTERS WITH
SELECTED RN_1 VALUES

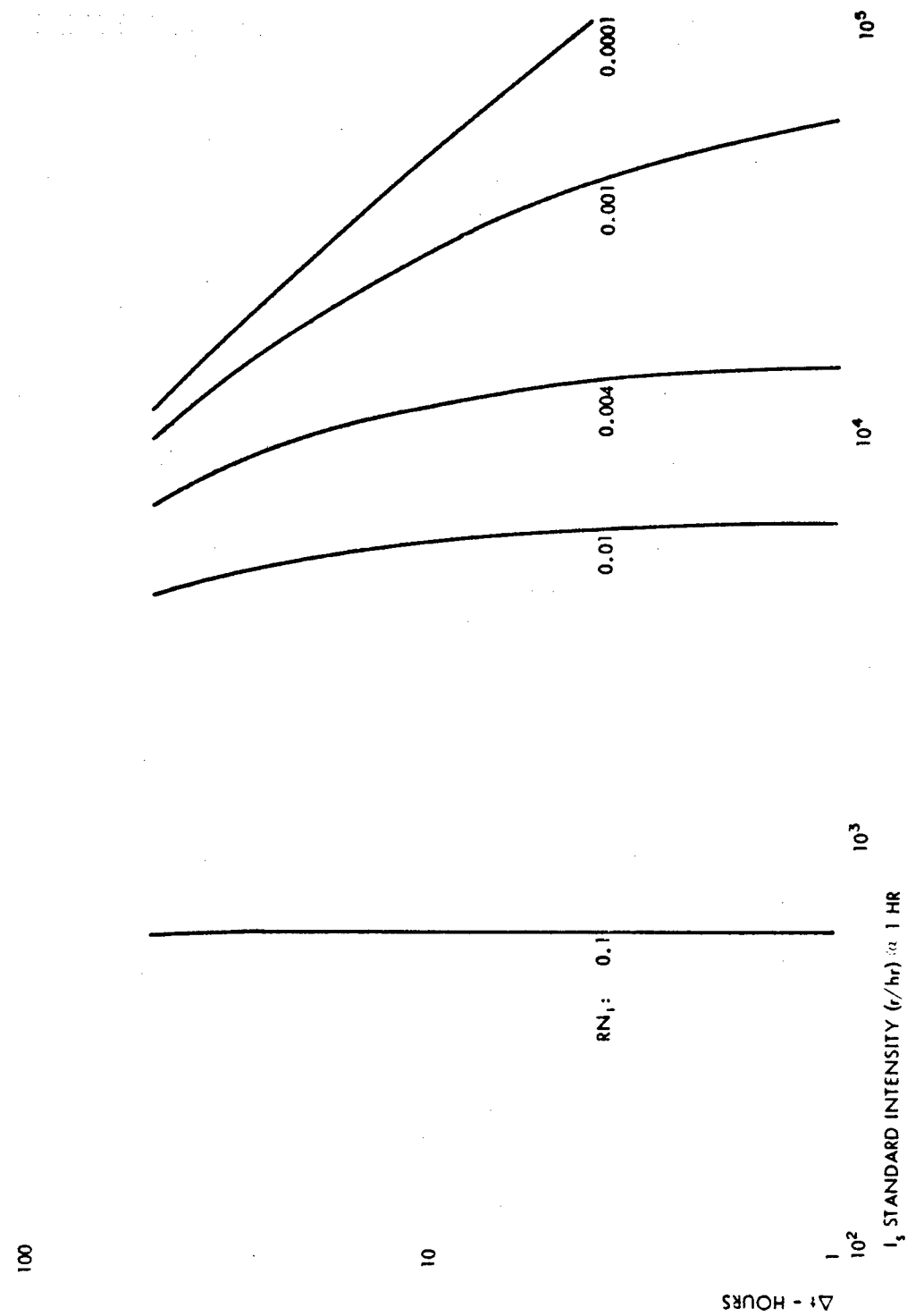


Figure 27

MAXIMUM TIMES ALLOWED FOR EVACUATION OR DECONTAMINATION
STARTING AT THIRTY DAYS AFTER ATTACK FROM SHELTERS WITH
SELECTED RN_1 VALUES

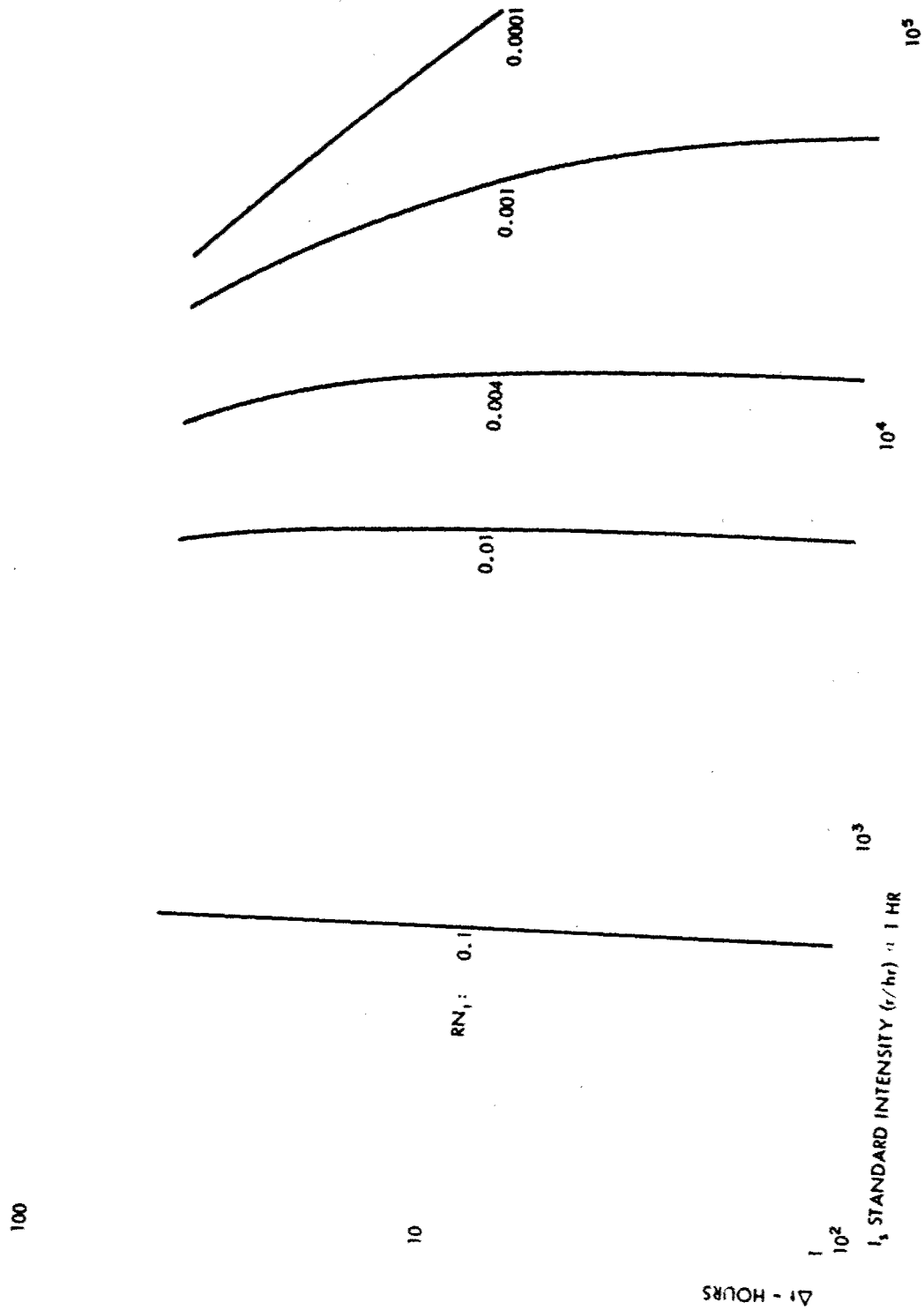


Figure 28

MINIMUM STARTING TIMES FOR
EVACUATION OR DECONTAMINATION
FOR VARIOUS VALUES OF I_s AND
ELAPSED TIMES WITH $RN_1 = 0.1$

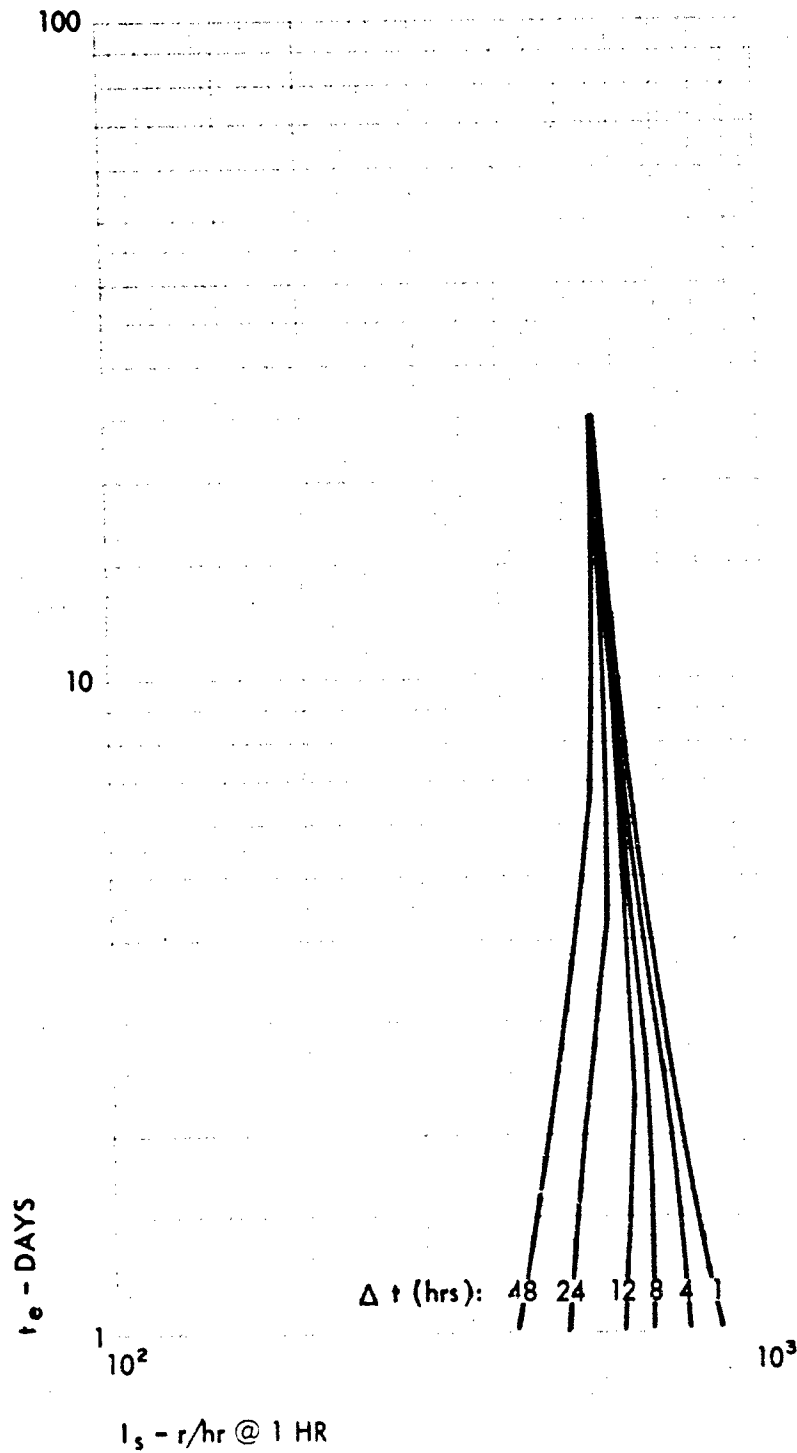


Figure 29

MINIMUM STARTING TIMES FOR EVACUATION OR
DECONTAMINATION FOR VARIOUS VALUES OF I_s AND
ELAPSED TIMES WITH $RN_1 = 0.01$

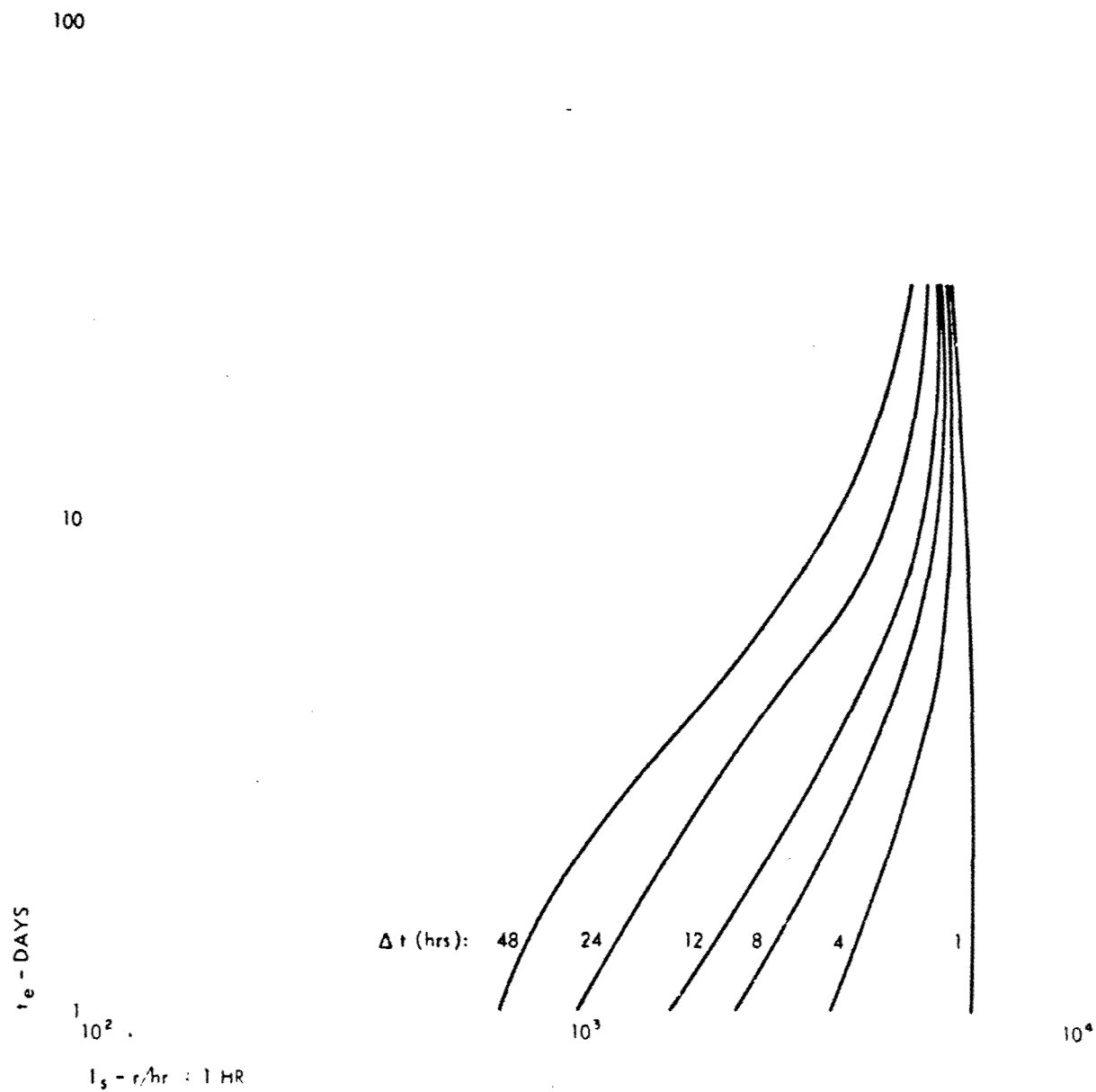


Figure 30

MINIMUM STARTING TIMES FOR EVACUATION OR
DECONTAMINATION FOR VARIOUS VALUES OF I_s
AND ELAPSED TIMES WITH $RN_1 = 0.001$

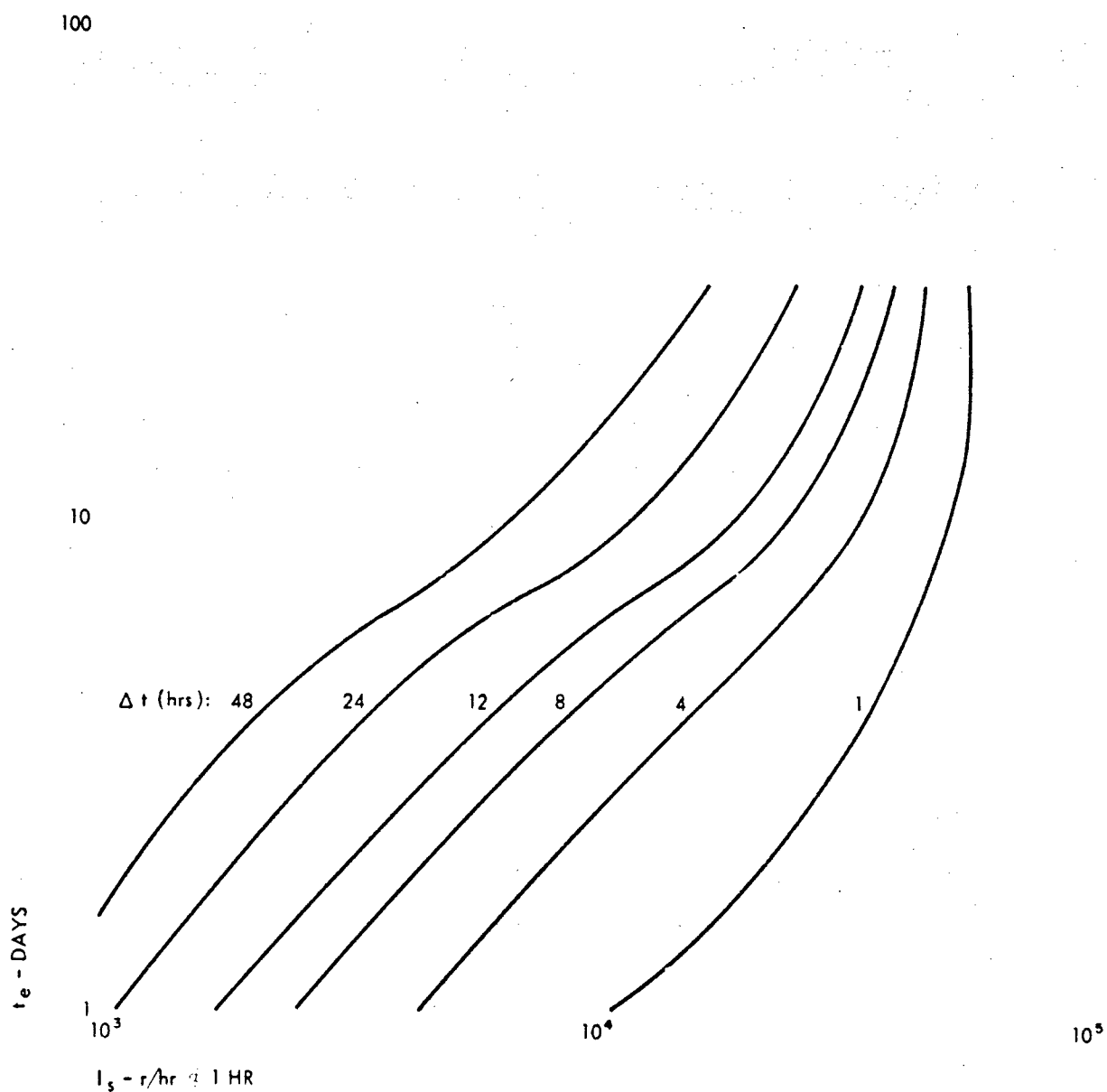


Figure 31

MINIMUM STARTING TIMES FOR EVACUATION OR DECONTAMINATION
FOR VARIOUS VALUES OF I_s AND ELAPSED TIMES WITH $RN_1 = 0.0001$

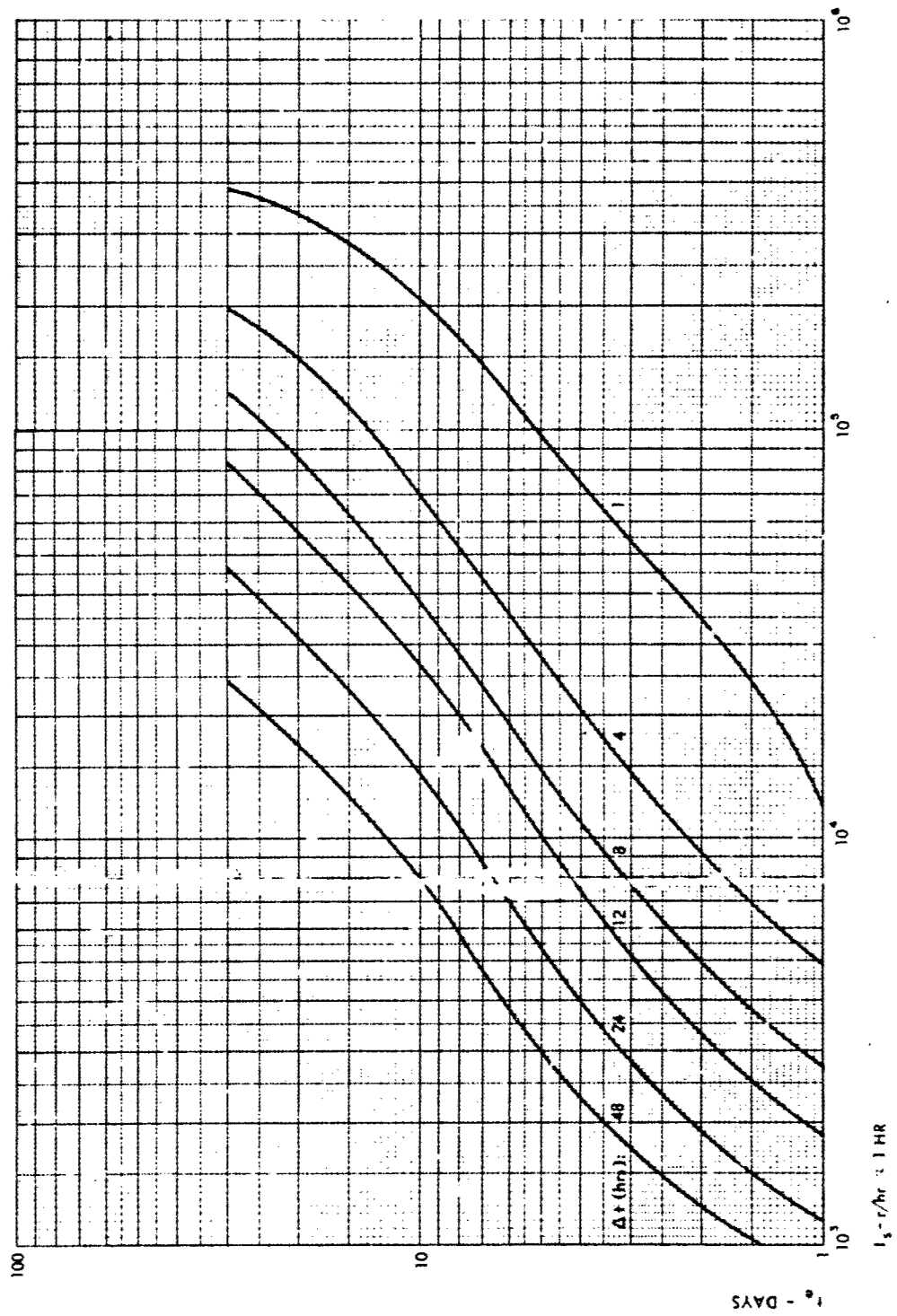


Figure 32

MINIMUM RE-ENTRY TIMES IN FALLOUT AREA
FOR VARIOUS SHELTER ROUTINES

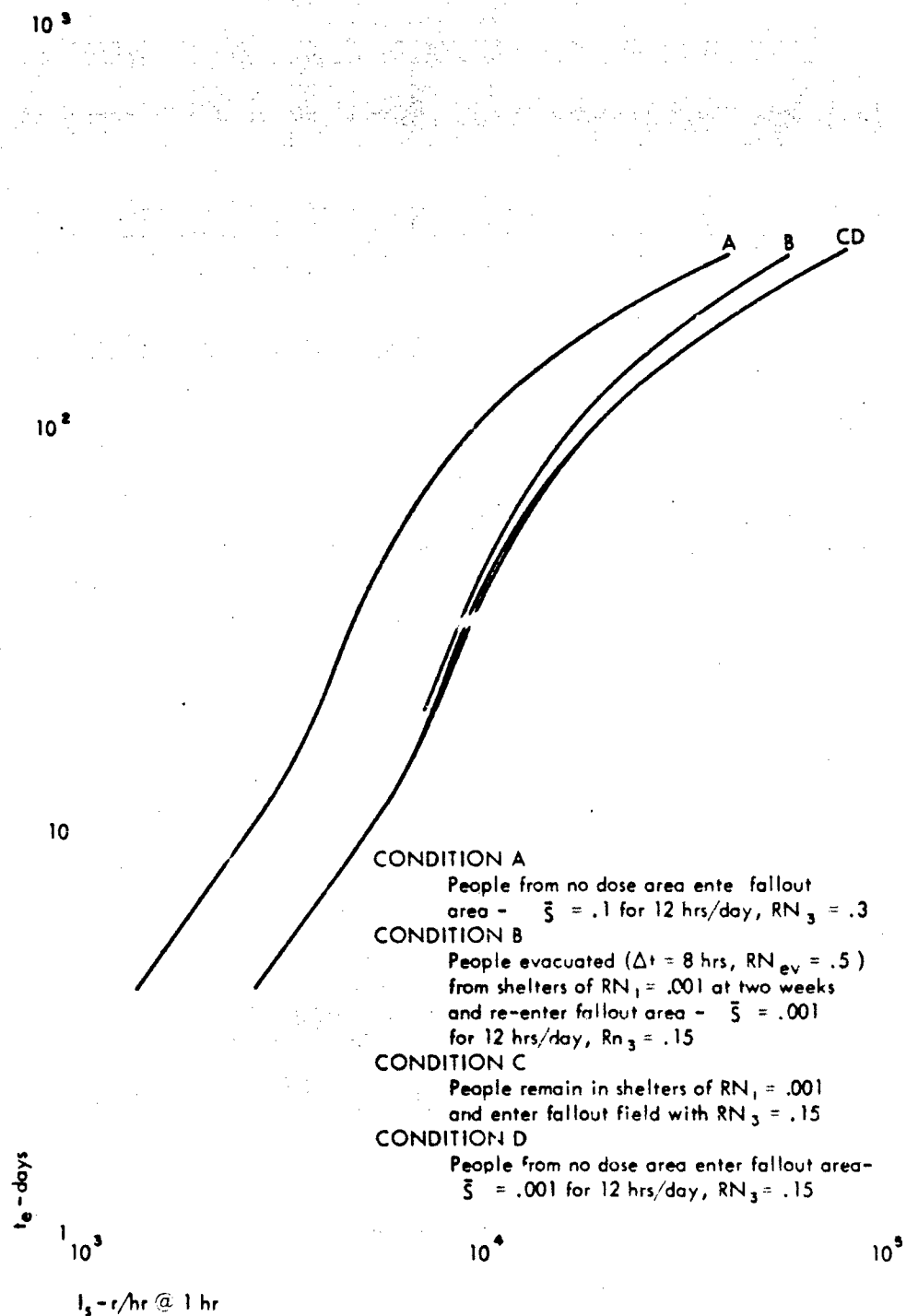
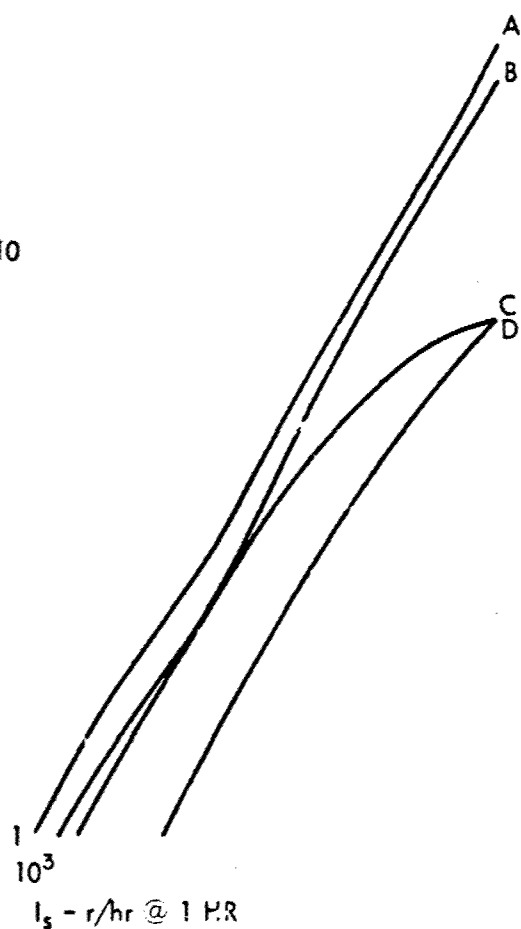


Figure 33

MINIMUM DECONTAMINATION START TIME FOR A THREE-PHASE
RADEF SYSTEM WITH $RN_1 = 0.01$

100

10



CONDITION A

$\Delta t_2 = 2-8$ hr decontamination
period on successive days
 $RN_2 = 0.7, RN_3 = 0.1$

CONDITION B

$\Delta t_2 = 8$ hrs of decontamination
 $RN_2 = 0.7, RN_3 = 0.1$

CONDITION C

$\Delta t_2 = 2-8$ decontamination
period on successive days
 $RN_2 = 0.7, RN_3 = 0.01$

CONDITION D

$\Delta t_2 = 8$ hrs of decontamination
 $RN_2 = 0.7, RN_3 = 0.01$

10^4

10^5

Figure 34

MINIMUM DECONTAMINATION START TIME FOR A THREE-PHASE RADEF SYSTEM WITH $RN_1 = 0.001$

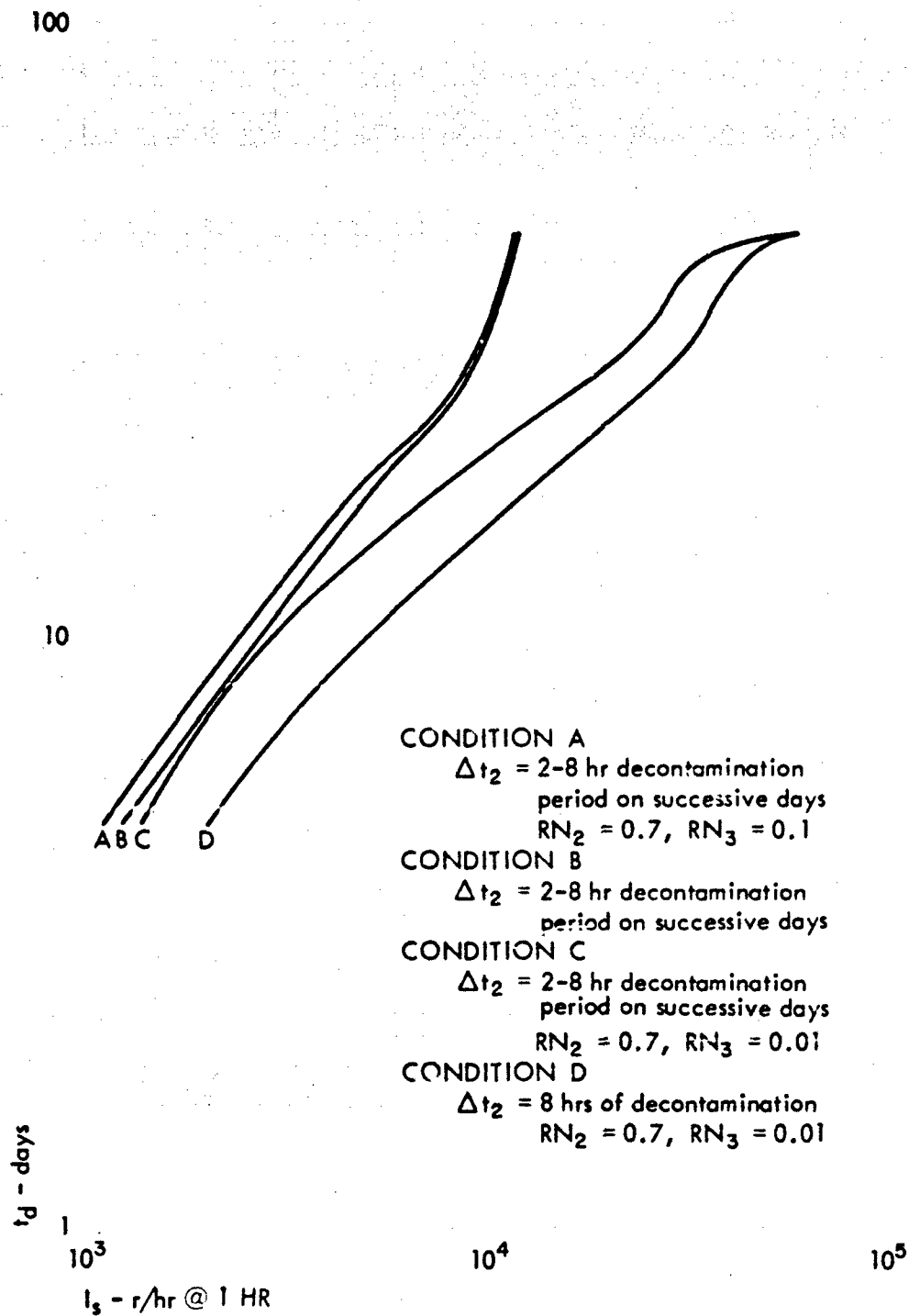


Figure 35

STANDARD INTENSITY CORRECTION TERMS
FOR FALLOUT ARRIVAL TIMES LONGER THAN
ONE HOUR AFTER DETONATION FOR RN_1
AND RN_3 REQUIREMENTS AND SHELTER-STAY
TIMES:

$$I_s(\bar{t}_a) = I_s \left\{ \frac{[RN_3 + a(1) RN_1]}{[RN_3 + a(t) RN_1]} \right\}$$

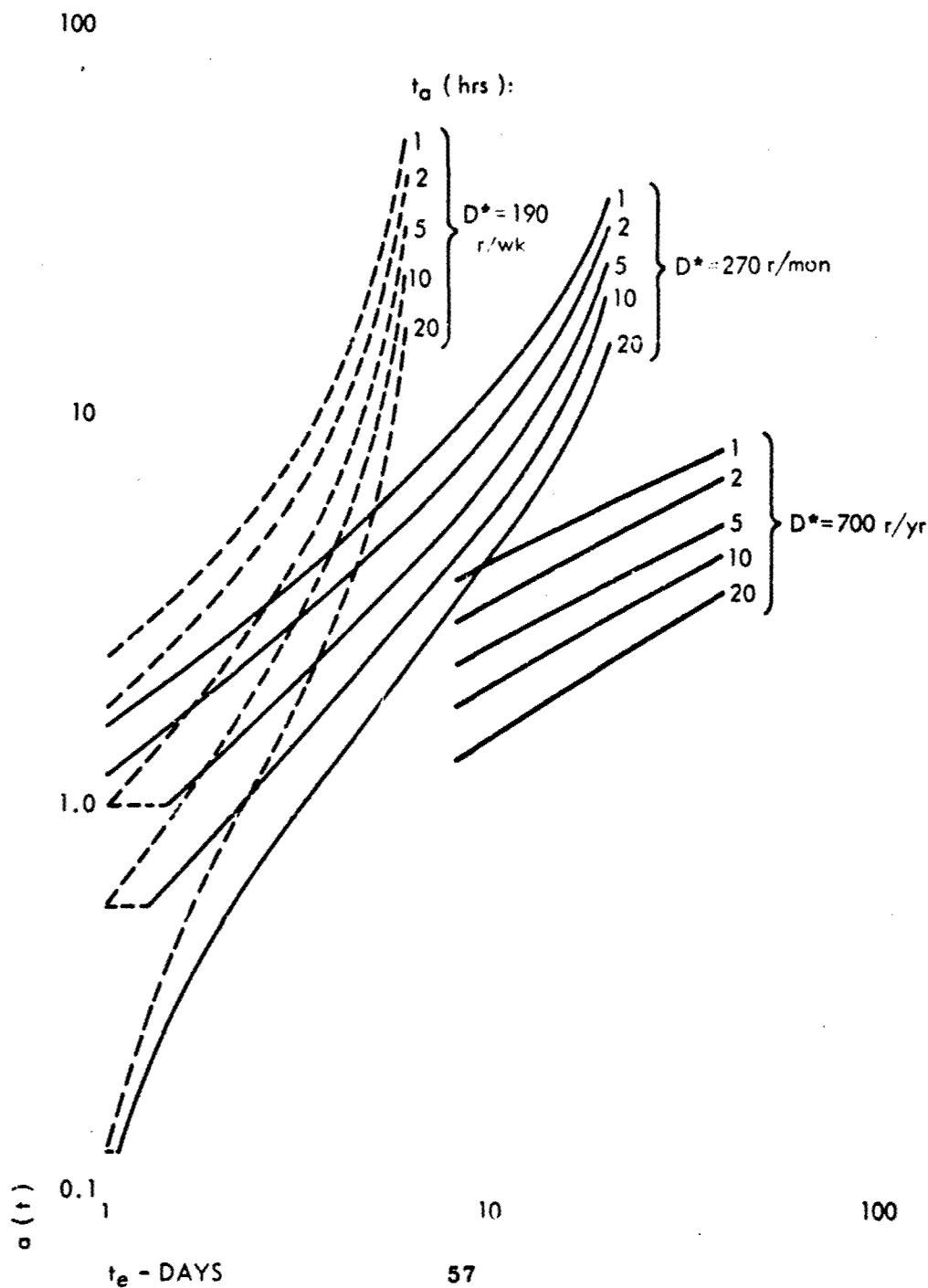
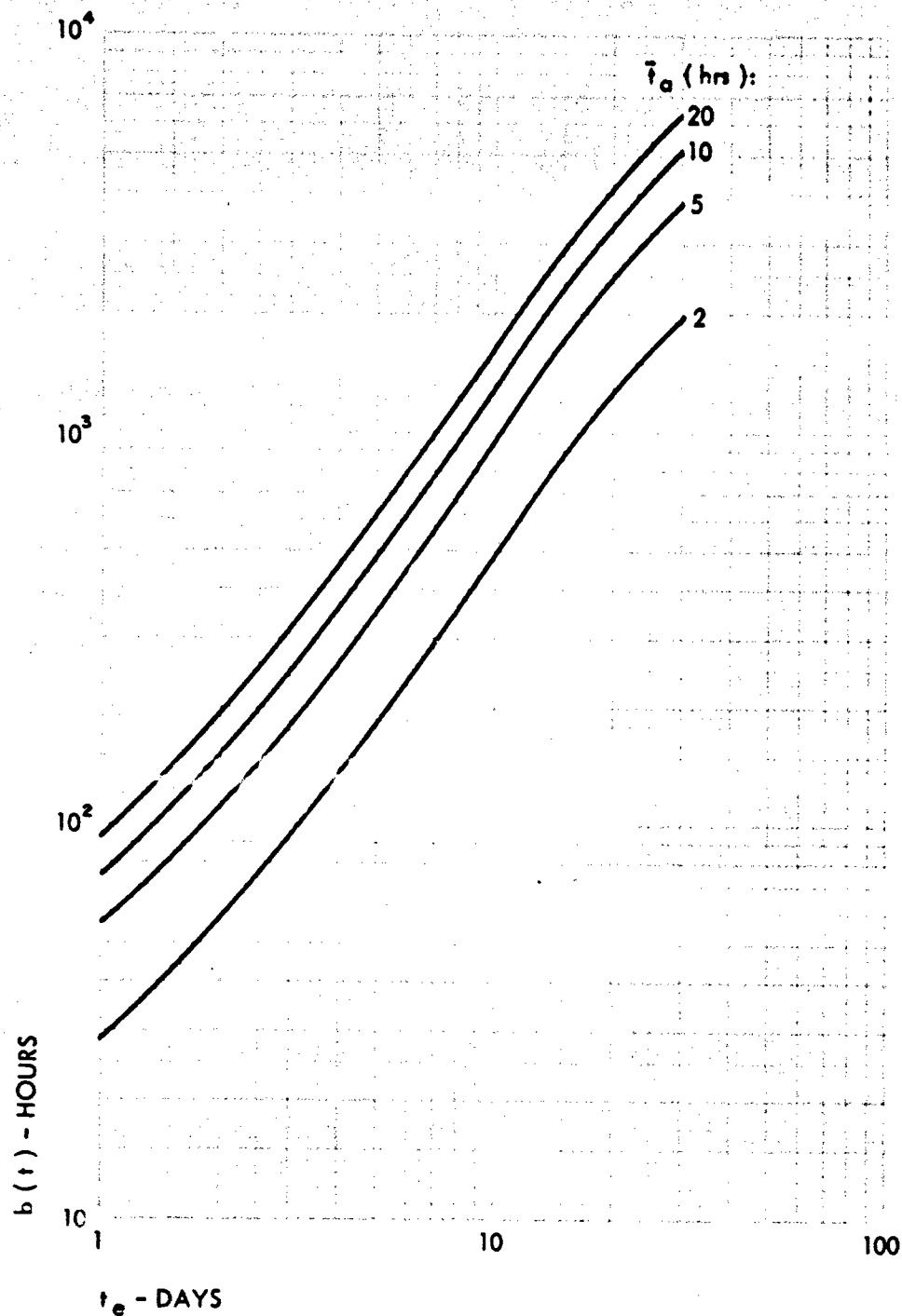


Figure 36

CORRECTION TERMS FOR MAXIMUM TIMES
ALLOWED FOR EVACUATION OR DECONTAM-
INATION FOR FALLOUT ARRIVAL TIMES
LONGER THAN ONE HOUR AFTER DETONATION



REFERENCES

1. Miller, Carl F., Fallout and Radiological Countermeasures, Volume II, Stanford Research Institute, Project IMU-4021, January 1963
2. Exposure to Radiation in an Emergency, National Committee on Radiation Protection Measurements, Report No. 29, January 1962